Water Working Notes

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WATER AND CLIMATE CHANGE: IMPACTS ON GROUNDWATER RESOURCES AND ADAPTATION OPTIONS

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ABBREVIATIONS AND ACRONYMS

AAA	Advisory and analytic activities
ACRA	Country Adaptation to Climate Risk Assessment
ADWR	Arizona Department of Water Resources
AFR	Africa Region
AMCOW	African Minister's Council on Water
AOGCM	Atmospheric-Ocean General Circulation Model
AS/NZS	Australian Standards/New Zealand Standards
ASR	Aquifer Storage and Recovery
ASTR	Aquifer Storage, Treatment and Recovery
AWS	Assured Water Supply
CAP	Central Arizona Project
CAS	Country Assistance Strategy
CC	Climate Change
CDM	Clean Development Mechanism
CEIF	Clean Energy for Development Investment Framework
CF	Carbon Finance
COP	Conference of the Parties
CO_2	Carbon dioxide
CPIA	Country Policy and Institutional Assessment
CSIRO	Commonwealth Scientific and Industrial Research Organization (Australia)
DEC	Development Economics Department
DPL	Development policy lending
EAP	East Asia and the Pacific
ECA	Europe and Central Asia
ECHAM4	Fourth-generation atmospheric general circulation model developed at the Max Planck Institute for Meteorology (MPI)
ENSO	El Niño-Southern Oscillation
ESMAP	Energy Sector Management Assistance Program
4AR	Fourth Assessment Report (IPCC)
FAR	First Assessment Report (IPCC)
GCM	General Circulation Model
GDE	Groundwater Dependent Ecosystem
GDP	Gross domestic product
GEF	Global Environment Facility
GHG	Greenhouse gases
GL	Giga liter
GMA	Groundwater Management Area
GNI	Gross National Income
GPG	Global public good
GRAPHIC	Groundwater resource assessment under the pressures of humanity and climate changes
GSS	Gnangara Sustainability Strategy
GWSP	Global Water System Project
HadCM3	Hadley Centre Coupled Model, Version 3
IAH	International Association of Hydrogeologists
IBRD	International Bank for Reconstruction and Development
IDA	International Development Association
IFC	International Finance Corporation
IGRAC	International Groundwater Resources Assessment Centre
IHP	International Hydrological Programme
IOD	Indian Ocean Dipole
IPCC	Intergovernmental Panel on Climate Change
IPO	Interdecadal Pacific Oscillation
IWSS	Integrated Water Supply System
km	Kilometer
LCR	Latin America and the Caribbean
MAR	Managed Aquifer Recharge
MCA	Multi-Criteria Analysis
MCE	Multiple Criteria Evaluation
MDG	Millennium Development Goals
MIGA	Multilateral Investment Guarantee Agency
ML	Mega liter
MNA	Middle East and North Africa
MOSES	Met Office Surface Exchange Scheme
NAO	North Atlantic Oscillation
NAPA	National Adaptation Programme of Action
NVB	Newer Volcanic Basalt
ODA	Official Development Assistance
PCL	Port Campbell Limestone
PCMDI	Program for Climate Model Diagnostics and Intercomparison
PPIAF	Public-Private Infrastructure Advisory Facility
ppm	parts per million
PPP	Public-Private Partnership
PRSP	Poverty Reduction Strategy Paper

PSDI	Palmer Drought Severity Index
RCM	Regional Climate Model
SADC	South African Development Community
SAR	Second Assessment Report (IPCC)
SAR	South Asia Region
SCCF	Special Climate Change Fund
SD	Statistical Downscaling
SEA	Strategic Environmental Assessment
SKM	Sinclair Knight Merz
SRES	Special Report on Emissions Scenarios
SSA	Sub-Saharan Africa
STP	Sewage treatment plant
SWAp	Sectorwide approach
TA	Technical assistance
TAR	Third Assessment Report (IPCC)
UK	United Kingdom
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
WA	Western Australia
WBG	World Bank Group
WGHM	WaterGAP Global Hydrology Model
WDR	World Development Report

EXECUTIVE SUMMARY

Adaptation to climate impacts on groundwater resources in developed and developing countries has not received adequate attention. This reflects the often poorly understood impacts of climate change, the hidden nature of groundwater and the general neglect of groundwater management. Many developing countries are highly reliant on groundwater. Given expectations of reduced supply in many regions and growing demand, pressure on groundwater resources is set to escalate. This is a crucial problem and demands urgent action.

This report addresses the impacts of climate change on groundwater and adaptation options. It is an abbreviated version of a larger report prepared by Sinclair Knight Merz (SKM)[1] for the World Bank as a special paper for the Water Anchor flagship Climate Change and Water. The larger report will also form one of several thematic papers for the new global groundwater governance project that is under preparation by the World Bank.

The importance of groundwater in a changing climate

The Earth's climate is projected to become warmer and more variable. Increased global temperatures are projected to affect the hydrologic cycle, leading to changes in precipitation patterns and increases in the intensity and frequency of extreme events; reduced snow cover and widespread melting of ice; rising sea levels; and changes in soil moisture, runoff and groundwater recharge. Increased evaporation and the risk of flooding and drought could adversely affect security of water supply, particularly surface water. Due to these pressures, as well as global population growth, demand for groundwater is likely to increase.

Compared to surface water, groundwater is likely to be much more compatible with a variable and changing climate. Relative to surface water, aquifers have the capacity to store large volumes of water and are naturally buffered against seasonal changes in temperature and rainfall. They provide a significant opportunity to store excess water during high rainfall periods, to reduce evaporative losses and to protect water quality. However these opportunities have received little attention, in part because groundwater is often poorly understood and managed.

Reducing vulnerability through adaptation

Groundwater plays a critical role in adapting to hydrologic variability and climate change. Groundwater options for enhancing the reliability of water supply for domestic, industrial, livestock watering and irrigation include (but are not exclusive to):

- *Integrating the management of surface water and groundwater resources* – including conjunctive use of both groundwater and surface water to meet water demand. Integrated management aims to ensure that the use of one water resource does not adversely impact on the other. It involves making decisions based on impacts for the whole hydrologic cycle.
- *Managing aquifer recharge (MAR)* – including building infrastructure and/or modifying the landscape to intentionally enhance groundwater recharge. MAR is among the most promising adaptation opportunities for developing countries. It has several potential benefits, including storing water for future use, stabilizing or recovering groundwater levels in over-exploited

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[1] Sinclair Knight Merz (SKM). 2009. Adaptation options for climate change impacts on groundwater resources. Victoria. Australia. The larger report: (a) characterizes the impact of current and projected hydrologic variability and Climate Change on groundwater, (b) develops a Methodology for Assessing Vulnerability and Risk in Groundwater Dependent Water Systems to Hydrological Variability and Climate Change and (c) presents four developed nation case studies from Australia, Europe, and the United States. The methodology for assessing vulnerability and risk developed under the larger report was omitted in the abbreviated report in order to avoid confusion with the methodology presented in the flagship report.

aquifers, reducing evaporative losses, managing saline intrusion or land subsidence, and enabling reuse of waste or storm water.

- *Land use change* – changing land use may provide an opportunity to enhance recharge, to protect groundwater quality and to reduce groundwater losses from evapotranspiration. Changes in land use should not result in adverse impacts to other parts of the environment.

Groundwater is also vulnerable to climate change and hydrological variability. Potential climate risks for groundwater include reduced groundwater recharge, sea water intrusion to coastal aquifers, contraction of freshwater lenses on small islands, and increased demand. Groundwater can also be affected by non-climatic drivers, such as population growth, food demand and land use change. Active consideration of both climatic and non-climatic risks in groundwater management is vital.

Effective decision making

Effective, long term adaptation to climate change and hydrologic variability requires measures which protect or enhance groundwater recharge *and* manage water demand. Adaptation to climate change can't be separated from actions to improve management and governance of water reserves (e.g. education and training, information resources, research and development, governance and institutions).

Adaptation needs to be informed by an understanding of the local context, and of the dominant drivers (and their projected impact) on groundwater resources in the future. Adaptations must be carefully assessed to ensure investment in responses to climate change and hydrological variability is proportional to risk and that they do not inappropriately conflict with other social, economic, resource management or environmental objectives. Adaptations should not add further pressures on the global climate system by significantly increasing greenhouse gas emissions.

Adaptation options need to be economically viable. In some cases the cost and benefits of an adaptation option may warrant introducing fees/charges for groundwater use, so that an appropriate level of cost recovery is met. An economic assessment of adaptation options should factor any initial and ongoing costs, and means for financing these. It must also take into account the local economic environment, which can vary significantly between and within nations.

Adaptation can start now

In many cases, adaptations to reduce the vulnerability of groundwater dependent systems climatic pressures are the same as those required to address non-climatic pressures, such as over-allocation or overuse of groundwater. Such 'no regrets' adaptations can be implemented immediately in areas where water resources are already stressed, regardless of concerns about the uncertainty of climate change projections and assessments of impact on groundwater and surface water resources.

Successful examples of groundwater adaptation to climate change and hydrologic variability exist in both developed and developing nations. A list of available adaptation options is included in this report. Adaptation case studies from three developed nations (England, America and Australia) are also provided.

Recommendations

To improve the Bank and client country capacity for and uptake of groundwater adaptation, the following next steps are recommended:

1. **Support adaptation case studies in developing nations** – adaptation case studies from three developed nations were reviewed in the current report. As part of the global groundwater governance project and the Bank's sector analysis on groundwater governance project, a series of case studies and evaluations are recommended to be prepared for developing countries. Possible case study countries could include: Peru, India, Kenya, Mexico, Morocco, Tunisia, South Africa, Tanzania and Yemen. The following transboundary

aquifers might also be considered to be part of these case studies:

- the Nubian sandstone aquifer system – this aquifer is located in north-eastern Africa and spans the political boundaries of four countries: Chad, Egypt, Libya and Sudan;
- aquifers that span across the fourteen countries in the South African Development Community (SADC).

These case studies would provide policy and operational guidance (lessons and experiences) to water resource managers in similar settings on improving groundwater governance and conceptualizing and implementing adaptation programs. As a minimum the case studies should focus on examples of MAR, improved management of groundwater storage, conjunctive use, planning and management of groundwater and surface water and reform of water governance. The case studies should cover a range of biophysical and institutional settings and be representative of different kinds of experienced climate change or climate risk impact.

2. **Promote groundwater management and development opportunities** – identify and integrate opportunities to manage and develop groundwater in future water sector programs to improve the reliability of water supply for multiple uses and protection of ecosystems. This may include supporting:

    - Assessment of the suitability of MAR – to determine the potential viability for MAR. This assessment should identify areas of current water stress (i.e. need), water availability (e.g. excess wet season surface flows, treated waste water), potential storage, and the likelihood that groundwater quality will be suitable for the required use/s. Any planning for MAR should be coupled with demand management strategies.
    - Capacity building in groundwater management and planning. This may include activities such as groundwater resource assessments to better understand the resource, establishing and populating groundwater databases, increasing the level of hydrogeological expertise by establishing or improving accessibility to groundwater training institutions, a manual for groundwater management to outline minimum good practice standards etc.
    - More integrated management of water resources. This may include conjunctive water use and assessing the impacts of existing or proposed infrastructure to identify any potential inefficiencies or adverse impacts that may be treated to achieve optimal use of water resources.

3. **Disseminate knowledge** - Information from this report and developing country case studies should be disseminated to World Bank staff as part of the overall sector analysis on Climate Change and Water.

4. **Collaborate with programs and partner agencies with specialized knowledge—**including:

    - Groundwater Resources Assessment under the Pressures of Humanity and Climate Change (GRAPHIC)—the GRAPHIC project is hosted by IHP UNESCO, IGRAC and GWSP and focuses on understanding the impacts of climate change and other pressures for groundwater, globally;
    - International Association of Hydrogeologists (IAH), and
    - International Groundwater Resource Assessment Centre (IGRAC)

1. INTRODUCTION

There is understandable concern about the potential impacts of human-induced climate change on water resources. While at a global level rainfall should increase due to increased evaporation, this change will be unevenly distributed and many regions are projected to receive substantially less rain (IPCC, 2007). When combined with increased temperatures, the retreat of glaciers, rising sea levels and increasing demand for fresh water from rapidly growing populations, the pressure on water resources is set to escalate.

Concern about climate change and water resources has translated into an impressive array of studies of potential impacts and adaptations. However, in comparison to surface water resources, the level of attention paid to groundwater, particularly in developing countries, has been limited. This reflects the hidden nature of groundwater, the general neglect of its management, as well as uncertainties about the potential impacts of climate change.

This report – Water and Climate Change: Impacts on groundwater resources and adaptation options—has been prepared as a special paper for the World Bank flagship on Climate Change and Water. The flagship covers Climate Change and Water issues from a broad and multi-sectoral perspective. This report is an abbreviated version of a larger report prepared by SKM for the World Bank[2]. The larger report will also form one of the thematic papers for the global groundwater governance project that is under preparation by FAO and the World Bank.

1.1 Groundwater in World Bank regions

Groundwater and soil moisture collectively account for over 98% of global fresh water resources, with more than two billion people dependent on groundwater for their daily supply (Hiscock, 2005). Groundwater is a major source of water for agriculture and to meet basic human needs in developing countries.

While not the dominant source of water in any of the six World Bank regions, groundwater is the major source in several countries (Table 1.1). Groundwater is most intensively developed in the World Bank's Middle East – North Africa and Latin America-Caribbean regions.

The hidden nature of groundwater, its resilience in the face of short-term climatic variability and the difficulty in measuring it, have, among other factors, contributed to its poor management and the growing stress on groundwater resources. In many countries, even developed countries with robust surface water management arrangements, groundwater use is unregulated and poorly planned and managed. Unsustainable management has resulted in the depletion of groundwater in both developed and developing nations (Figure 1.1). Usage often exceeds average annual recharge. In some North African and Middle East nations, water use exceeds recharge by a factor of three (IGRAC, 2004; http://igrac.nitg.tno.nl/ggis_map/start.html).

Pressures on surface water resources are intensifying, due to growth in population, increased demand for food, pollution and (in some regions) climate change. As this occurs, these pressures are increasingly being referred to groundwater and the need for improved management grows.

Groundwater also plays an important role in sustaining a wide range of terrestrial, aquatic and marine ecosystems. For some ecosystems, there is a highly specialized dependency on groundwater; for example for habitat, water supply or survival during drought (e.g. Hatton and Evans, 1998; Clifton and Evans, 2001).

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[2] The larger report: (a) characterizes the impact of current and projected hydrologic variability and Climate Change on groundwater, (b) develops a Methodology for Assessing Vulnerability and Risk in Groundwater Dependent Water Systems to Hydrological Variability and Climate Change and (c) presents four developed nation case studies from Australia, Europe, or the United States. The methodology for assessing vulnerability and risk developed under the larger report was omitted in the abbreviated report in order to avoid confusion with the methodology presented in the flagship report.

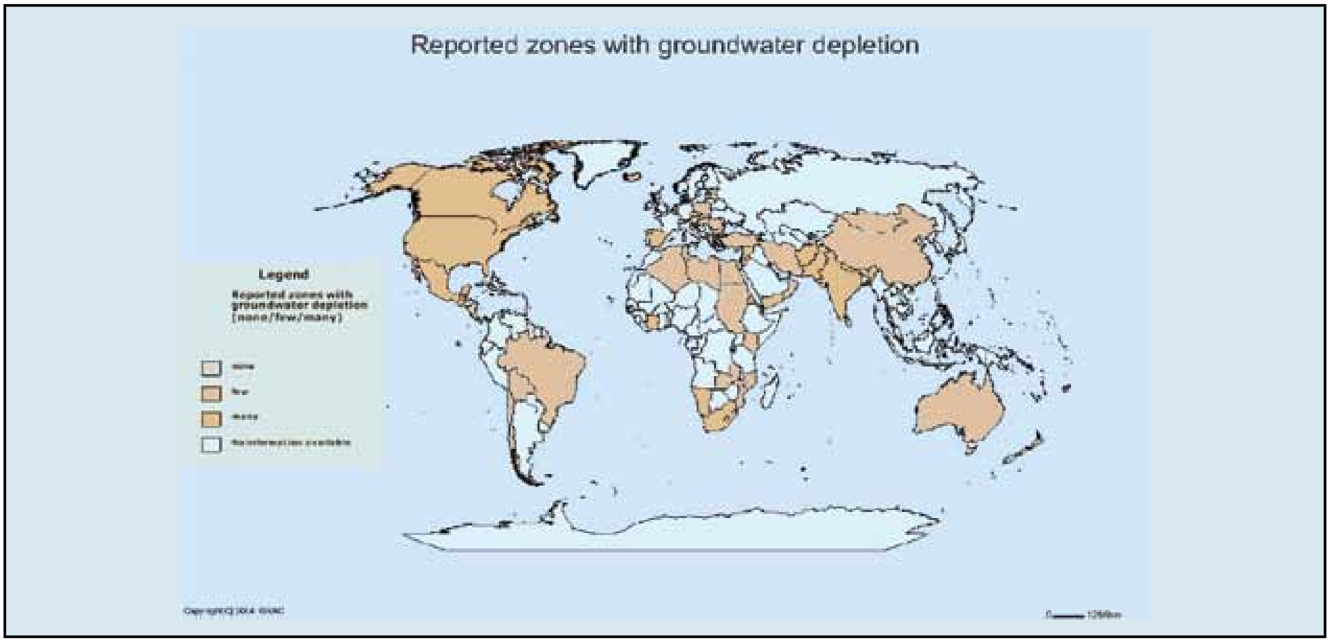
Table 1.1: Groundwater use in World Bank Regions

	Groundwater use as % of total water use		Examples of countries where >50% of water is sourced from groundwater
World Bank region	Average % use across region[1]	Maximum recorded percentage of use	
East Asia and Pacific	19	79	Mongolia
Europe and Central Asia	22	83	Georgia, Lithuania.
Latin America and the Caribbean	32	96	Barbados, Bolivia, Jamaica.
Middle East and North Africa	41	78	Iran, Libya, Tunisia.
South Asia	26	35	-
Africa	18	54	Botswana, Mauritania, Namibia.

Source data: IGRAC

[1] Where data available.

Figure 1.1: Reported Countries with Groundwater Depletion



Source: IGRAC Global Groundwater Information System: http://igrac.nitg.tno.nl/ggis_map/start.html

1.2 Climate change

Atmospheric concentrations of carbon dioxide and other greenhouse gases are increasing. There is a growing body of evidence that this is already contributing to changes in climatic conditions, with impacts on hydrological cycles evident at some locations (IPCC, 2007). Global change scenarios anticipate further large increases in greenhouse gas emissions over the course of this century, with consequences for climate including increased surface temperature, changes in the amount and pattern of precipitation and increased potential evaporation. The nature of these changes is projected to vary across the globe. The critical threats to groundwater (and dependent systems) from these changes is reduced availability of groundwater, due to reduced groundwater recharge, increased demand or groundwater contamination (Section 2.2). The implications for socio-economic and environmental conditions in vulnerable regions could be very serious. There is a 'basic need to identify the sensitivity of groundwater to climate variability and change' (GRAPHIC, 2008). Adaptation is required to address the risks faced and improve the resilience of groundwater dependent communities and environments.

1.3 About this report

This report is a special paper for the Water Anchor flagship Climate Change and Water. Its overall objective is to develop an analytical framework for improving the resilience of groundwater dependent communities and environments in the face of threats from increasing demand, unsustainable management and reduced availability due to climate change. A broader goal of the paper is also to promote and elevate the role of groundwater in integrated water resources management (IWRM).

The analysis of the impacts of climate change on groundwater and adaptation was planned to be carried out in two phases. The first phase is reported here. It includes a literature review of the current and projected impact of hydrologic variability and climate change on groundwater and of adaptation options for groundwater resources. A methodology for assessing vulnerability and risk to hydrologic variability and climate change in groundwater dependent water systems has also been developed and is part of the larger report. Several case studies have been prepared, which outline adaptations to improve the resilience of groundwater systems to climate change and hydrological variability in Australia, the United States of America and the United Kingdom.

This report also proposes the scope of subsequent phases which will be supported under the new global groundwater governance project and will (a) identify, assess and begin to implement adaptation options for improving the resilience of groundwater systems in selected developing nations and (b) disseminate project outputs to World Bank staff working in water supply, irrigation and water resources management.

The target audience is technical and non technical water supply, irrigation, water resources and environmental specialists from the Bank, other institutions and client nations.

This report is structured as follows:

Section 1: Introduction – briefly summarizes the context, purpose and scope of the project

Section 2: Climate change, hydrological variability and groundwater – a review of the linkages between groundwater and climate, the impacts of climate change on groundwater resources, and implications for groundwater dependent systems. A discussion of the existing knowledge status and identified data and knowledge gaps is also included.

Sectionr 3: Adaptation options – a review and assessment of adaptation options to improve the resilience of groundwater systems to risks posed by hydrological variability and climate change.

Section 4: Case studies – a summary of three case examples where groundwater adaptation options have been employed.

Section 5: Conclusion

Section 6: Recommendations

2. CLIMATE CHANGE, HYDROLOGICAL VARIABILITY AND GROUNDWATER

2.1 Fundamental concepts

2.1.1 Groundwater and the hydrologic cycle

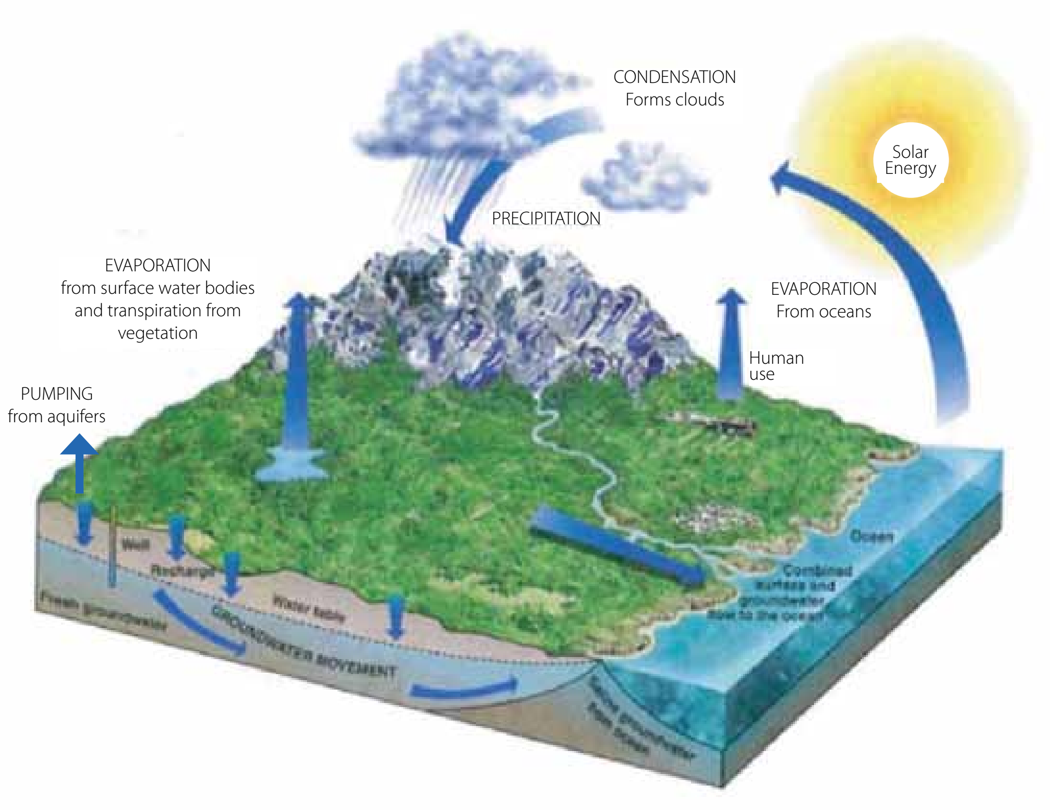
The *hydrologic cycle* (Figure 2.1) represents the continuous movement of water between the atmosphere, the Earth's surface (glaciers, snowpack, streams, wetlands and oceans) and soils and rock. The term *groundwater* refers to water in soils and geologic formations that are fully saturated.

The hydrologic cycle is driven by solar energy which heats the Earth's surface and causes water from the Earth's surface to evaporate, sublimate and transpire. Water is transported from the atmosphere back to the Earth's surface as precipitation, falling as either rain or snow.

Exchange of atmospheric water to groundwater can occur via infiltration of rainfall or snowmelt through the soil profile. Water may also run off the Earth's surface and infiltrate to groundwater via stream channels and wetlands. The process by which water from the surface enters the groundwater system is called *recharge*.

Loss of groundwater to the atmosphere occurs through the process of evapotranspiration. This includes direct

Figure 2.1: The Hydrologic Cycle



Source: http://www.pvwma.dst.ca.us/hydrology/images/hydrologic_cycle.jpg evaporation of shallow groundwater and transpiration by vegetation. Groundwater may also flow into streams, springs, wetlands and oceans, or be pumped from wells for human use. The process by which water is lost from groundwater is called *discharge*. The difference between recharge and discharge determines the volume of water in groundwater storage.

Any variations in climate have the potential to affect recharge, discharge and groundwater quality, either directly or indirectly. An example of a direct impact would be reduced recharge due to a decrease in precipitation. Sea water intrusion to coastal aquifers due to increased temperature and subsequent sea level rise represents an indirect influence on groundwater quality.

Groundwater quantity and quality can also be affected by water and land use change. Examples include changes to groundwater pumping regimes, damming of rivers, clearing of woody vegetation and conversion of dryland agriculture to irrigation.

2.1.2 Climate change and hydrologic variability

Climate change is "an altered state of the climate that can be identified by change in the mean and/or variability of its properties and that persist for an extended period, typically decades or longer" (Bates et al., 2008). It may be due to "natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use" (IPCC, 2007).

Over the past 150 years global mean temperatures have increased with the rate of warming accelerated in the past 25 to 50 years. It is considered very likely that this change is largely attributed to anthropogenic influences (in particular increased CO_2 concentrations from burning of fossil fuels) and that global warming will continue in the future (IPCC, 2007).

Climate also varies in response to natural phenomena, on seasonal, inter-annual, and inter-decadal scales. Examples of these natural phenomena include the El Nino Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), the North Atlantic Oscillation (NAO) and the Interdecadal Pacific Oscillation (IPO). The presence of, and degree of influence from, these and other natural phenomena will vary between countries and even watersheds.

Variations in climate will induce hydrologic change. Table 2.1 summarizes the variations in climate and hydrology that are projected to occur due to global warming. The potential impacts of these changes for groundwater resources are discussed in subsequent sections.

2.2 Impacts of climate change on groundwater

2.2.1 Recharge

Groundwater recharge[3] can occur locally from surface water bodies or in diffuse form from precipitation via the unsaturated soil zone (Döll and Fiedler, 2008). Precipitation is the primary climatic driver for groundwater recharge. Temperature and CO_2 concentrations are also important since they affect evapotranspiration and thus the portion of precipitation that may drain through the soil profile to aquifers. Other factors affecting groundwater recharge include land cover, soils, geology, topographic relief and aquifer type.

The only global scale estimates of climate change impacts to groundwater recharge are those developed by Döll and Florke (2005). Based on calculations from the global hydrological model WGHM (WaterGAP Global Hydrology Model), they estimated diffuse recharge (1961–1990 baseline) at the global scale with a resolution of 0.5° by 0.5°. They then simulated the impacts of climate change for 2050s under a high (A2) and low (B2) greenhouse gas emission scenario. Other scenarios (e.g. 2030 time frame, A1B greenhouse gas emissions) were not modeled in this work and therefore cannot be reported here.

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[3] The focus of this section is on natural recharge, not artificial recharge. Artificial recharge occurs due to excess irrigation or via intentional enhancement of recharge. The latter is commonly known as managed aquifer recharge (MAR). MAR is discussed further in Section 3.4.1.

Table 2.1: Projected Impact of Global Warming for Primary Climate and Hydrologic Indicators

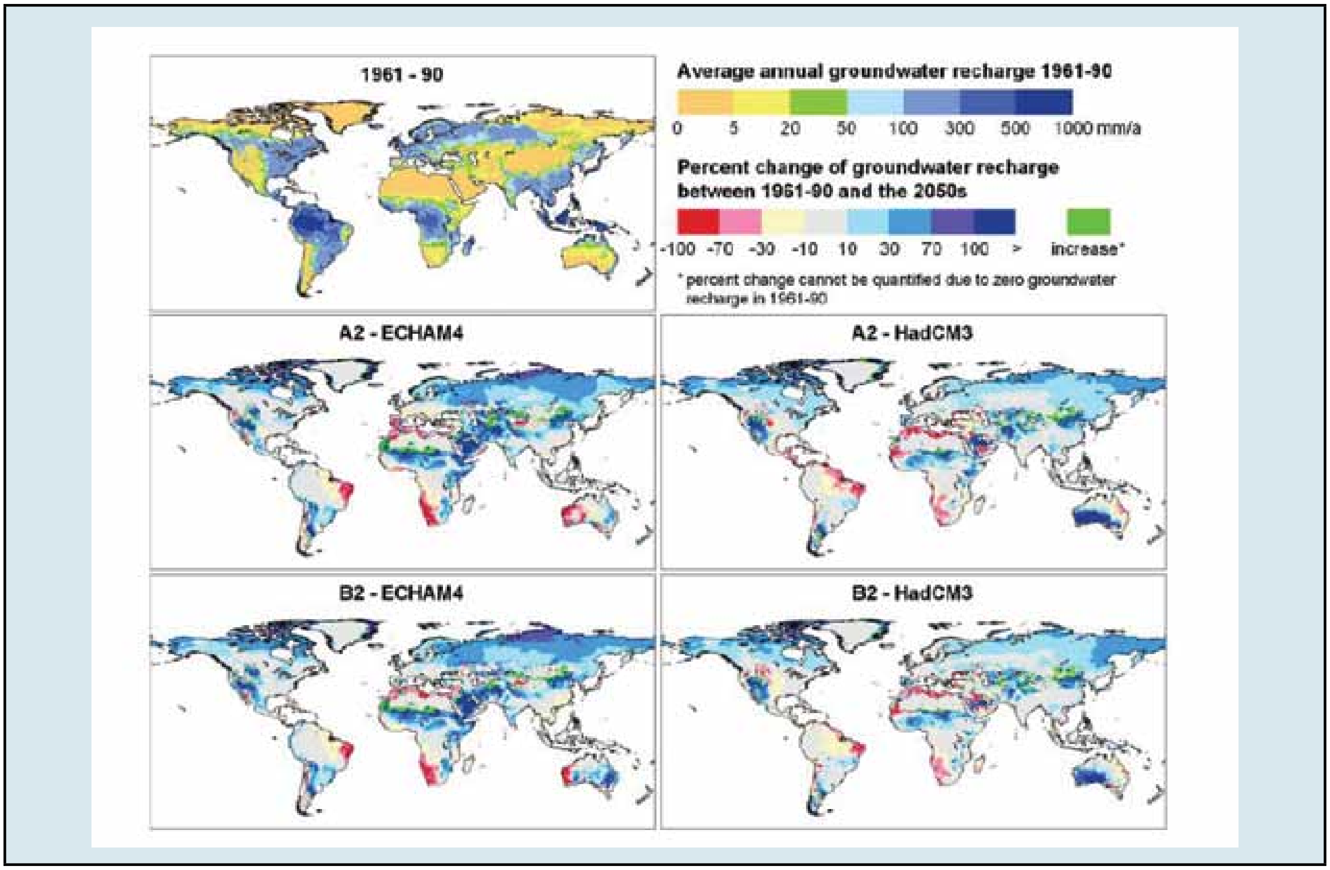
Variable	Projected future change*
Temperature	Temperatures are projected to increase in the 21st century, with geographical patterns similar to those observed over the last few decades. Warming is expected to be greatest over land and at the highest northern latitudes, and least over the Southern Oceans and parts of the North Atlantic ocean. It is very likely that hot extremes and heat waves will continue to become more frequent.
Precipitation	On a global scale precipitation is projected to increase, however this is expected to vary geographically—some areas are likely to experience an increase and others a decline in annual average precipitation. Increases in the amount of precipitation are likely at high latitudes. At low latitudes, both regional increases and decreases in precipitation over land areas are likely. Many (not all) areas of currently high precipitation are expected to experience precipitation increases, whereas many areas of low precipitation and high evaporation are projected to have precipitation decreases. Drought-affected areas will probably increase and extreme precipitation events are likely to increase in frequency and intensity. The ratio between rain and snow is likely to change due to increased temperatures.
Sea level rise	Global mean sea level is expected to rise due to warming of the oceans and melting of glaciers. The more optimistic projections of global average sea level rise at the end of the 21st century are between 0.18–0.38 m, but an extreme scenario gives a rise up to 0.59 m. In coastal regions, sea levels are likely to also be affected by larger extreme wave events and storm surges.
Evapo-transpiration	Evaporative demand, or potential evaporation, is influenced by atmospheric humidity, net radiation, wind speed and temperature. It is projected generally to increase, as a result of higher temperatures. Transpiration may increase or decrease.
Runoff	Runoff is likely to increase at higher latitudes and in some wet tropics, including populous areas in East and South-East Asia, and decrease over much of the mid-latitudes and dry tropics, which are presently water stressed. Water volumes stored in glaciers and snow cover is likely to decline, resulting in decreases in summer and autumn flows in affected areas. Changes in seasonality of runoff may also be observed due to rapid melting of glaciers and less precipitation falling as snow in alpine areas.
Soil moisture	Annual mean soil moisture content is projected to decrease in many parts of the sub-tropics and generally across the Mediterranean region, and at high latitudes where snow cover diminishes. Soil moisture is likely to increase in East Africa, central Asia, the cone of South America, and other regions with substantial increases in precipitation.

*Relative to 1990 baseline. Source: IPCC (2007), World Bank (2009)

According to the results of Döll and Florke (2005), recharge—when averaged globally for the 2050s—will increase by 2%. This is less than the projected increases of 4% and 9% for annual precipitation and runoff. Geographical variations in Döll and Florke's (2005) 2050 recharge projections (Figure 2.2) include:

- significant decreases in groundwater recharge (by more than 70%) for north-eastern Brazil, the western part of southern Africa and areas along the southern rim of the Mediterranean Sea
- increased groundwater recharge (by greater than 30%) across large areas, including the Sahel, Northern China, Western US and Siberia

Figure 2.2: Global Estimates of Climate Change Impact on Groundwater Recharge



Impact of climate change on long-term average annual diffuse groundwater recharge. Percent changes of 30-year averages groundwater recharge between 1961–1990 and the 2050s (2041–2070), as computed by WGHM applying four different climate change scenarios (climate scenarios computed by the climate models ECHAM4 and HadCM3, each interpreting the two IPCC greenhouse gas emissions scenarios A2 and B2). Source: Döll and Florke (2005).

- potentially significant decreases in groundwater recharge for Australia, USA and Spain, although results vary significantly between climate models in these areas.[4]

These global estimates identify regions where groundwater is potentially vulnerable to climate change. However, they are not appropriate for scaling down to a country or watershed scale. Precipitation and groundwater systems can vary significantly between watersheds and this variability has not been incorporated into Döll and Florke's (2005) modeling. Also, their method only represents diffuse recharge—recharge from rivers or other surface waters were not accounted for.

Changes in the magnitude of groundwater recharge will not always be in the same direction as precipitation changes. Recharge is not only influenced by the magnitude of precipitation, but also by its intensity, seasonality, frequency, and type (Figure 2.3). Other factors, for example changes in soil properties or vegetation type and water use can also affect recharge rates. van Roosmalen et al. (2007) concluded that changes to groundwater recharge rates were highly dependent on the geological setting of the area.

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[4] This is relative to 1961–1990 recharge rates which in many cases may be very low. Uncertainties associated with projected change in precipitation from global climate model models also apply here.

Figure 2.3: Summary of Climate Change Impacts on Recharge under Different Climatic Conditions

High latitude regions	Temperate regions	Arid and semi-arid regions
Recharge may occur earlier due to warmer winter temperatures, shifting the spring melt from spring toward winter.In areas where permafrost thaws due to increased temperatures, increased recharge is likely to occur	Changes to annual recharge will vary depending on climate and other local conditions. In some cases little change may be observed in annual recharge, however the difference between summer and winter recharge may increase	In many already water stressed arid and semi arid areas, groundwater recharge is likely to decrease.However where heavy rainfalls and floods are major sources of recharge, an increase in recharge may be expected. E.g., alluvial aquifers where recharge occurs via stream channels, or bedrock aquifers where recharge occurs via direct infiltration of rainfall through fractures or dissolution channels.

Source: Holman et al, 2001; Döll and Florke, 2005; van Vliet, 2007; Dragoni and Sukhija, 2008.

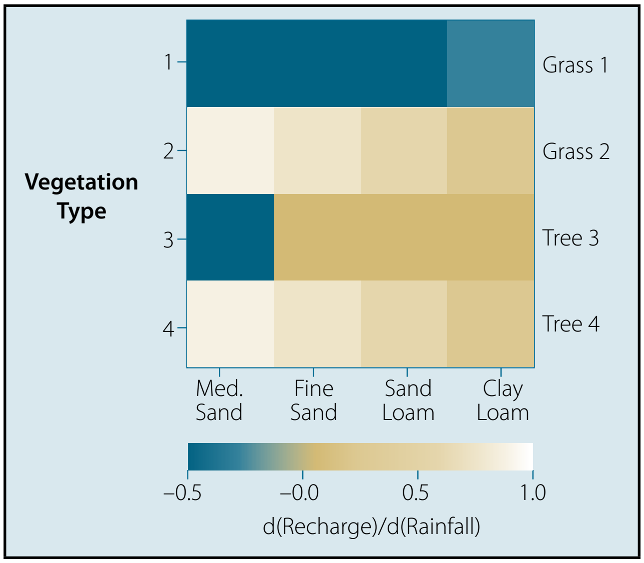
During high intensity rainfall events the infiltration capacity of soils may quickly be exceeded, resulting in increased runoff and stream flow with less rain infiltrating to groundwater (Acreman, 2000). More frequent and longer droughts may lead to soil crusting and hydrophobic soils, such that during precipitation events overland flow increases and groundwater recharge decreases (Döll and Florke, 2005). In areas where groundwater is recharged from surface water bodies or via preferential pathways such as macropores and joints, higher intensity rainfall is likely to lead to more groundwater recharge (Döll and Florke, 2005; van Vliet, 2007).

Precipitation changes during the major recharge season are likely to be more significant than annual changes. Yet this will also be influenced by antecedent conditions on a seasonal and inter-annual scale. More frequent droughts or reduced rainfall during summer months can result in larger soil moisture deficits, and consequently recharge periods may be shortened (Acreman, 2000; Holman, 2006; Döll and Florke, 2005). This may be exacerbated by increased temperatures and evapotranspiration, although the effects of climate change on transpiration from vegetation is uncertain (Section 2.2.2).

In high latitude regions, recharge may occur earlier as warmer winter temperatures shift the spring melt from spring toward winter (van Vliet, 2007). Where permafrost thaws due to increased temperatures, increased recharge is likely to occur (Dragoni and Sukhija, 2008).

The ratio of change in groundwater recharge to change in rainfall is not 1:1. Green et al. (1997) simulated the effects of climate change on groundwater recharge in the Gnangara Mound, Western Australia, by modeling the impacts of increased atmospheric concentrations of CO_2 on rainfall and potential evapotranspiration regimes. They found that the magnitude and even the direction of change in recharge depends on the local soil, vegetation and climatic region and that ratios of the change in recharge to change in rainfall ranged from –0.8 to 0.6 (Figure 2.4).

Figure 2.4: Simulated Change in Recharge per Unit Change in Rainfall under a Double-CO_2 climate change Scenario in Western Australia (Green et al., 1997)

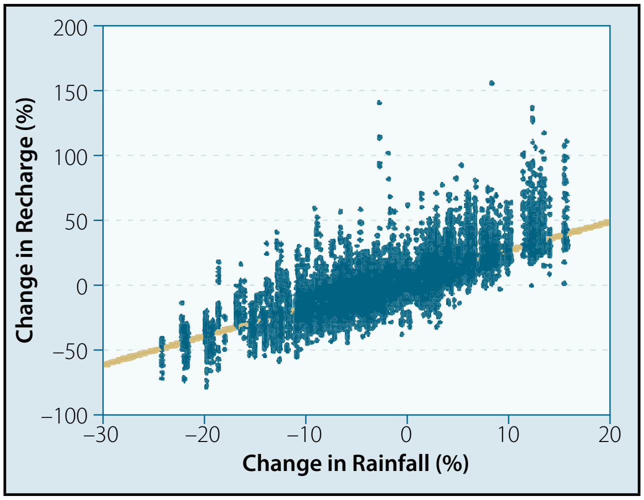


Grasses 1 and 2 represent perennial grasses, Trees 1 and 2 represent pine and eucalypt canopies. Reproduced from GRAPHIC (2008).

For the Hawkesdale region in south-eastern Australia, SKM (2007) modeled the impacts of climate change on groundwater recharge under different land cover, depth to water table, geological and climatic conditions. The latter included capturing natural inter-decadal variations in climate, in addition to anthropogenic climate change (further details are provided in the larger report). Across their modeled scenarios, ratios of the change in recharge to change in rainfall ranged from 0 to 0.87. Where rainfall fell below the threshold required to negate runoff and evapotranspirative losses, zero recharge was observed to occur.

Sandstorm (1995) studied a semi-arid basin in Africa and concluded that a 15% reduction in rainfall could lead to a 45% reduction in groundwater recharge. In the Murray Darling Basin (Australia) Crosbie et al. (2009) also concluded that the percentage change in groundwater recharge was greater than the percentage change in rainfall, by a factor of approximately 2.2 (Figure 2.5). Furthermore Crosbie et al. (2009) found that even when there is no change in rainfall, the increase in temperature caused an increase in the vapour pressure deficit, which resulted in an increase in evapotranspiration and hence a decrease in recharge. The decrease in recharge manifested itself as reduced discharge to streams and hence reduced streamflow. This has very significant implications.

Figure 2.5: Change in Rainfall Versus Change in Recharge for Murray Darling Basin, Australia



Source: Crosbie et al., 2009.

2.2.2 Discharge

The impacts of climate change on groundwater discharge are less well understood. In part this reflects the difficulties in measuring discharge, and thus a lack of data to quantify discharge processes (van Vliet, 2007). Historically groundwater assessments have also been focused on understanding how much water enters the groundwater system and if this is suitable for human use. Less consideration has been given to the ecosystems groundwater supports, such as terrestrial vegetation and groundwater flow to springs, streams, wetlands and oceans.

For evapotranspiration, direct climate change impacts include: (1) changes in groundwater use by vegetation due to increased temperature and CO_2 concentrations, and (2) changes in the availability of water to be evaporated or transpired, primarily due to changes in the precipitation regime.

Whilst CO_2 is likely to be a significant factor in the water balance, the extent of its impact is still uncertain (Kurijt et al., 2008). Experimental evidence shows that elevated atmospheric CO_2 concentrations tend to reduce stomatal opening in plants, and that this leads to lower transpiration rates (Bethenod et al., 2001; Kurijt et al., 2008). In a study for the Netherlands, Kruijt et al. (2008) concluded that the combined effects of CO_2 on evapotranspiration ranged between a few percent for short crops to about 15% for tall rough vegetation, and that this was of a 'comparable but opposite magnitude to predicted temperature-induced *increases* in evapotranspiration'.

Increased duration and frequency of droughts (due to increased temperatures and increased variation in precipitation) is likely to result in greater soil moisture deficits. Where soil water becomes depleted, vegetation may increasingly depend on groundwater for survival (if groundwater occurs in proximity to the root zone). During dry periods this may lead to increased evapotranspiration from groundwater. Indirect impacts associated with land use change may also affect groundwater evapotranspiration. For example, reforestation for CO_2 capture may draw on shallow groundwater and lower water tables (Dragoni and Sukhija, 2008).

Groundwater flow to surface water bodies will be driven by relative head levels between groundwater and surface water. Consequently the affects of climate change are indirect; through alterations to recharge and other discharge mechanisms (e.g. evapotranspiration). If groundwater falls below surface water levels, groundwater discharge may no longer occur (and vice versa). In semi-arid and arid regions, the dependence on groundwater to maintain baseflow in permanent streams is likely to be greater during periods of extended drought. In temperate areas where higher winter recharge is projected (e.g. UK) it is conceivable that some watersheds could sustain higher baseflows during summer, even if summers become warmer and drier (Acreman, 2000).

Groundwater pumping also forms a mechanism for groundwater discharge. Projected increases in precipitation variability are likely to result in more intense droughts and floods, affecting the reliability of surface water supplies with respect to both quantity and quality. Human demand for groundwater is therefore likely to increase to offset this declining surface water availability and, where available, will become a critical facet for communities to adapt to climate change (Foster, 2008).

Large volumes of groundwater, often of acceptable quality, discharge to oceans in near shore environments. This discharge process, and the capacity for recovery of groundwater, is currently poorly understood (Dragoni & Sukhija, 2008).

2.2.3 Groundwater storage

Groundwater storage is the difference between recharge and discharge over the time frames that these processes occur, ranging between days to thousands of years. Storage is influenced by specific aquifer properties, size and type. Deeper aquifers react, with delay, to large-scale climate change but not to short-term climate variability. Shallow groundwater systems (especially unconsolidated sediment or fractured bedrock aquifers) are more responsive to smaller scale climate variability (Kundzewicz and Döll, 2008). The impacts of climate change on storage will also depend on whether or not groundwater is renewable (contemporary recharge) or comprises a fossil resource.

2.2.4 Water quality

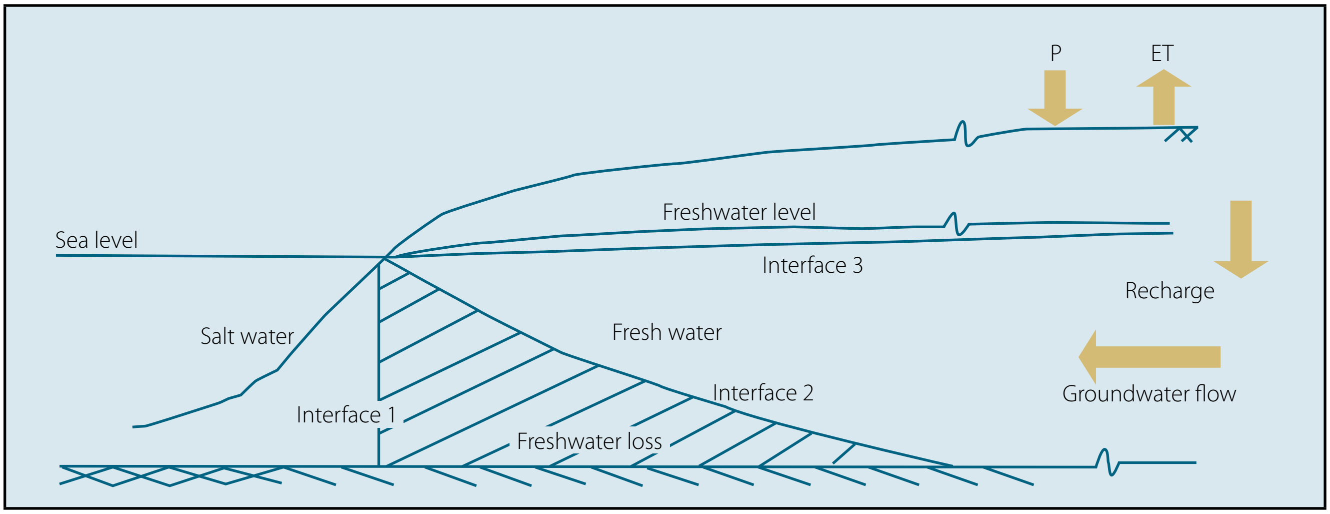
In many areas, aquifers provide an important source of freshwater supply. Maintaining water quality in these aquifers is essential for the communities and farming activities dependent on them. Both thermal and chemical properties of groundwater may be affected by climate change. In shallow aquifers, groundwater temperatures may increase due to increasing air temperatures. In arid and semi-arid areas increased evapotranspiration may lead to groundwater salinization (van Vliet, 2007). In coastal aquifers, sea level rise and storm surges are likely to lead to sea water intrusion and salinization of groundwater resources. Changes in recharge and discharge (see above) are likely to change the vulnerability of aquifers to diffuse pollution (van Vliet, 2007).

Ranjan et al. (2006) assessed the impact of sea level rise on the loss of fresh groundwater resources in coastal aquifers. Their study included coastal areas in the following five regions: Central America, Southern Africa, Northern Africa/Sahara, around the Mediterranean, and in the Southern Asia. Climate change impacts were simulated for a high (A2) and low (B2) emissions scenarios and accounted for changes in groundwater recharge, as per the conceptual model provided in Figure 2.6. With the exception of the Northern Africa/Sahara region, Ranjan et al. (2006) found that a long-term trend of increasing loss of fresh coastal groundwater resources was likely in all studied regions under both high and low emissions scenarios. Small islands and coral atolls, where sea level rise leads to contraction of fresh groundwater lenses, are particularly vulnerable (Kundzewicz & Döll, 2008).

In areas where rainfall intensity is expected to increase, pollutants (pesticides, organic matter, heavy metals etc) will be increasingly washed from soils to water bodies (IPCC, 2007). Where recharge to aquifers occurs via these surface water bodies, groundwater quality is likely to decline. Where recharge is projected to decrease, water quality may also decrease due to lower dilution (IPCC, 2007) and in some cases may also lead to intrusion of poorer quality water from neighboring aquifers (van Vliet, 2007).

Taylor et al. (2008) assessed the impact of increased heavy rains on the water quality of spring discharge in Kampala,

Figure 2.6: Schematic Representing the Loss of Fresh Groundwater Resources Due to Saltwater Intrusion in Coastal Aquifers



Increases in recharge shifts the saltwater interface seaward. Decreases in recharge and/or increases in sea level will result in landward movement of the salt water interface. Source: Ranjan et al. (2006).

Uganda. They concluded that increased heavy rainfall events would lead to more frequent, episodic deterioration in bacteriological quality of spring discharges, derived from rapid flushing of inadequately contained fecal matter in the area. In areas where groundwater levels rise, waste stored underground in the unsaturated zone may become saturated and contaminate the groundwater resource.

2.3 Impacts of non-climatic factors

Whilst climate change is likely to have adverse impacts on the quantity and quality of groundwater resources, in many areas this will be dwarfed by the non-climatic impacts including growth in the global population, food demand (which drives irrigated agriculture), land use change, and socio-economic factors that influence the capacity to appropriately manage the groundwater resource.

Historically, in both developed and developing nations, groundwater demand has been poorly managed. Low investment in groundwater investigations and management during the 20th Century, a time of intensive groundwater use for agricultural crop production, has placed groundwater under stress (Hiscock and Tanaka, 2006). Increased groundwater use associated with population growth has also been a factor, particularly in arid and semi-arid areas where water is scarce. Future global population growth is expected to place groundwater resources under greater stress.

Land use change also affects groundwater resources. The degree and magnitude of impact will depend on local conditions. In a small Sahelian catchment in Niger, Seguis et al. (2004) found that the transition from a wet period under a 'natural' land cover (1950) to a dry period under cultivated land cover (1992) resulted in a 30 to 70% increase in runoff. Recharge in this catchment occurred preferentially through ponds, and thus the increased runoff caused a significant and continuous water table rise over the same period. In this catchment, Seguis et al. (2004) concluded that the impacts of land use change were more important than drought.

In a south-western Uganda catchment, clearing of vegetation has led to a 90% reduction in yields from local groundwater springs (Mutiibwa, 2008). The clearing has been driven by population growth and the need to cultivate and settle land. Loss of vegetation cover has resulted in less interception and infiltration of rainfall, and increased runoff.

The dominant recharge mechanism is direct infiltration of rainfall and therefore changes in the rainfall-runoff relationship have resulted in a significant reduction in groundwater recharge.

A range of technical and socio-economic factors have contributed to the current condition of groundwater resources, and these will influence their management in the future also. Inadequate information to inform groundwater allocation; lack of qualified personnel; increasing contamination of water resources from agriculture, industries and mining; uncontrolled groundwater abstraction; lack of land use planning; inadequate financial capacity and a lack of education and awareness amongst stakeholders are just some of the challenges that must be overcome (Kalugendo, 2008). Muttibwa (2008) concluded that the appropriate management of groundwater resources required not only a technical and financial capacity, but also 'political goodwill'.

2.4 Implications for groundwater dependent systems and sectors

Groundwater dependent systems comprise those communities, industries and environments that rely on groundwater for water supply. Dependence on groundwater in developing countries is high, due to either water scarcity or a lack of safe drinking water from surface water supplies. Climate change and other pressures may compromise the availability and quality of groundwater resources with significant implications for human and environmental health, livelihoods, food security and social and economic stability. Degradation of groundwater will also increase the susceptibility of poor communities to extreme events (Ranjan et al., 2006).

2.4.1 Rural and urban communities

Shallow wells often provide an important source of drinking water for rural populations in developing nations. Increased demand and potentially increased severity of droughts may cause these shallow wells to dry up. With limited alternatives for safe drinking water supplies (surface water may be absent or contaminated and deeper wells may not be economically feasible), loss of groundwater would force people to use unsafe water resources or walk long distances for water (Kongola, 2008). This has associated impacts for human health and the capacity (time) to earn an income or gain education.

The livelihoods of rural populations are largely dependent on land, water and the environment with limited alternatives compared to their urban counterparts. Reduced water availability can cause severe hardships. Drying up of pasture and drinking water to livestock can wipe out herds of livestock that are sources of income, family security and food. Small scale irrigation enterprises, usually reliant on shallow groundwater, may also fail (Kongola, 2008).

Where increases in heavy rainfall events are projected, floods can wash away sanitation facilities, spreading waste water and potentially contaminating groundwater resources. This may lead to increased risk of diarrheal disease (Taylor et al., 2008). The risk of such contamination is likely to be greater in urban areas due to higher population density and concentration of source pollutants. In coastal regions, sea water intrusion may limit the capacity of communities to cope with already large and rapidly expanding populations (Ranjan et al., 2006).

2.4.2 Agriculture

Globally, irrigated agriculture is the largest water use sector (Kundzewicz et al., 2007). In areas where the availability of groundwater is reduced, irrigation may become unviable, particularly if demand for drinking water supply in the area (a higher priority) cannot be met. Alternatively, irrigation may need to occur on an opportunistic basis during periods of water availability or adopt alternative water resources (such as recycled waste water), or technologies and methods for increased water use efficiency. In areas where groundwater availability increases, agriculture may benefit. However shallow rising water tables may also cause problems such as soil salinization and water logging.

2.4.3 Ecosystems

The impact of climate change is likely to accentuate the competition between human and ecological water uses, particularly during periods of protracted drought (Loaiciga, 2003). Environmental implications include the reduction or elimination of stream baseflow and refugia for aquatic plants and animals, dieback of groundwater dependent vegetation, and reduced water supply for terrestrial fauna. In areas where salinization occurs, e.g. coastal regions, salt sensitive species may be lost. Other sources of groundwater contamination may also adversely affect ecosystems.

2.5 Uncertainties and knowledge gaps

Quantifying impacts of climate change on groundwater is difficult and is subject to uncertainties in future climate projections (particularly precipitation) and the relative influence of other factors, e.g. vegetation response to change in carbon dioxide. Studies of climate change impacts on groundwater recharge have largely focused on quantifying the direct impacts of changing precipitation and temperature patterns, assuming other parameters remain constant (Holman, 2006). Few studies have addressed indirect climate effects such as change in land use, vegetation cover and soil properties (Holman, 2006; Jacques, 2006). Natural climate variability is also often ignored with the focus typically being on anthropogenic climate change impacts only.

To focus solely on the direct impacts of climate change arising from temperature and precipitation is to neglect the potentially important role of societal values and economic pressures in shaping the landscape above aquifers (Holman, 2006). To obtain more realistic predictions of hydrological response to the future climate, the impact of indirect consequences of climate changes—such as sea level rise, changes in agricultural practice and land use and the development in water demand for domestic and irrigation purposes—and natural climate variability also need to be addressed. This will require an integrated approach that considers the physical processes as well as describing the plausible human developments in the future (van Roosmalen *et al*., 2007).

There is significant uncertainty in the global recharge mapping (Döll and Florke, 2005). This is due to uncertainties in projected precipitation and the inability of the Döll and Florke's (2005) recharge modeling to capture preferential recharge from surface water bodies such as streams (Döll and Florke, 2005). Whilst providing an indicator of potentially vulnerable regions, this global mapping in not suitable for assessing vulnerability at national or watershed scales. Information and data at a sub-regional and groundwater basin level are required for operational and investment purposes.

Watershed case studies on global climate change are a matter of concern (Varis et al, 2004); however in many locations they will be constrained by a paucity of meaningful data. Many developing nations are data poor, and there are also many uncertainties and limitations associated with downscaling global climate models to this scale. There is a need for better database management and dissemination of information for water resource managers.

Current understanding of climate change impacts is poor. However there are a number of organizations beginning to enhance the understanding of climate change impacts on groundwater resources. This includes UNESCO's initiative Groundwater Resources Assessment under the Pressures of Humanity and Climate Changes (GRAPHIC), with which the International Groundwater Resource Assessment Centre (IGRAC) and the International Association of Hydrogeologists (IAH) Commission on Climate Change are partners. Whilst knowledge of climate change impacts for groundwater is advancing, there does not appear to be any coordinated approach for developing responses (adaptation).

GRAPHIC (2008) discuss additional knowledge and data gaps relevant to groundwater and climate change.

2.6 Groundwater vulnerability to climate change at a World Bank regional scale

A preliminary assessment of the vulnerability of groundwater in World Bank regions to climate change was undertaken to highlight any geographies with particularly low or high vulnerability to climate change. The assessment was developed by the authors using the basic criteria defined below. It assesses vulnerability for 2050 climate change scenarios, assuming all non-climatic conditions as current. The assessment is at regional scale and is intended as a general indicator only. As a high level assessment it might help guide priorities for further work to more precisely assess vulnerability to climate change and to build the resilience of groundwater dependent systems. It is not intended to assess country-scale priorities.

Four criteria were considered in the regional vulnerability indicator assessment (Table 2.2):

- sensitivity: current level of exploitation of groundwater resources – as indicated by the use of groundwater relative to average annual recharge (after IGRAC, 2004);
- exposure: the magnitude and trend in changes in rates of groundwater recharge under 2050 climate change projections (after Döll and Flörke, 2005);
- exposure: the exposure of regional water resources to sea level rise and contamination due to storm surge (based on the authors' assessment of cyclone incidence, the extent of coastal areas in the region and population density in these areas);
- adaptive capacity: wealth, as measured by per capita gross national income (GNI; World Bank, 2008[5])

Groundwater use is used as an indicator of sensitivity to climate change. The second and third criteria were indicators of exposure and GNI was used to indicate adaptive capacity. These factors were combined to provide a vulnerability indicator. Adaptive capacity and the combination of exposure and sensitivity indicators were weighted evenly. Weighting to sea level rise and storm surge risk was reduced to reflect its uneven application to World Bank regions.

While there remains significant uncertainty with this assessment, it suggests that groundwater in the World Bank Europe and Central Asia region is the least vulnerable to

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[5] Data from http://go.worldbank.org/GKIIAZEJR0

Table 2.2: Preliminary Assessment of Vulnerability of Groundwater in World Bank Regions to Climate Change

	Sensitivity	Exposure		Adaptive capacity	
World Bank region	Utilization of groundwater	Climate change impact on recharge	SLR[1] & storm surge exposure	Per capita GNI[1]	Vulnerability[2]
East Asia & Pacific	Moderate	Increase	Medium	Moderate	Moderate
Europe & Central Asia	Low	Increase	Low	High	Low
Latin America & Caribbean	Moderate	Reduction	Medium	Moderate	Moderate
Middle East & North Africa	High	Uncertain	Low	Moderate	Moderate
South Asia	Moderate	Negligible	High	Low	High
Africa	Moderate	Reduction	Low	Low	High

SLR – sea level rise; GNI – gross national income (in $US)
Vulnerability assessed from the sum of average of sensitivity and exposure ratings and adaptive capacity rating.
Groundwater utilization – low (2), moderate (4), high (6)
Impact on recharge – increase (2), uncertain/negligible (4), reduction (6)
SLR exposure – low (1), medium (2), high (3)
Per capita GNI – low (6), moderate (4), high (2) – relative to each other
Low vulnerability (<6), Moderate (6–9), High (>9)

the effects of climate change. This reflects the relatively low level of utilization of groundwater, the projected increase in rainfall (in many areas), minimal exposure of groundwater to risks from sea level rise and storm surge and higher per capita income. Groundwater resources in the South Asia and Africa regions were considered to be most vulnerable.

Country-to-country differences in vulnerability are expected to be large, with this regional scale analysis most likely masking important 'hot spots' of climate change vulnerability. A country level analysis, using similar criteria, but based on more definitive information is warranted to establish clearer priorities for further work. Such an assessment is beyond the scope of this review.

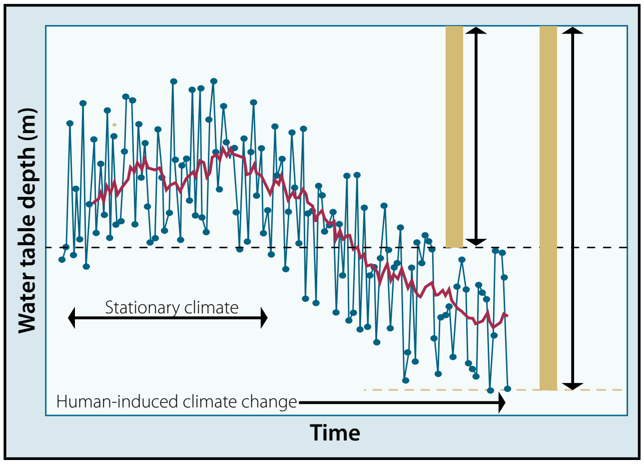
3. ADAPTATION TO CLIMATE CHANGE

3.1 Introduction

What is adaptation?

Groundwater dependent systems have the capacity to cope with some level of hydrological variability (in quality and quantity or water) without impairment (Figure 3.1). This 'coping range' varies with the sensitivity of the groundwater dependent system to changes in various groundwater attributes (e.g. water quality, depth, pressure, discharge flux). Extremes of natural climatic variability (e.g. prolonged climatic drought) may mean that some groundwater attributes fall outside the coping range of the system, resulting in socio-economic and/or environmental harm. In some areas, human-induced climate change threatens to change the hydrological environment such that its state is outside the system's coping range more frequently, potentially perpetuating that harm (Figure 3.1).

Figure 3.1: Coping Range and Adaptation to Human-Induced Climate Change (redrawn from Willows and Connell, 2003)



The graph shows variation in a hypothetical hydrological parameter (e.g. water level in shallow aquifer) under stationary conditions and human-induced climate change (the solid black line shows the mean state). In sequences of dry years, water levels may fall below the depth of a well or bore (which would define the system's coping range) and some form of harm is experienced. In this example, human-induced climate change is projected to initially result in increased frequency of years during which water levels fall below the level from which water can be extracted. As change progresses, this state becomes permanent. With adaptation (e.g. extending the well or sinking a deeper bore) the system's coping range is extended so that permanent harm is avoided. Note that adaptations are rarely required to respond to a single stimulus, such as in this example

Adaptations are adjustments made in natural or human systems in response to experienced or projected climatic conditions or their *beneficial* or *adverse* effects or impacts (Smit et al., 2001). In the context of this report (and Figure 3.1) they are concerned with reducing the vulnerability of groundwater dependent systems to climate change and hydrological variability. Adaptations are essentially management responses to risks associated with climate variability and climate change.

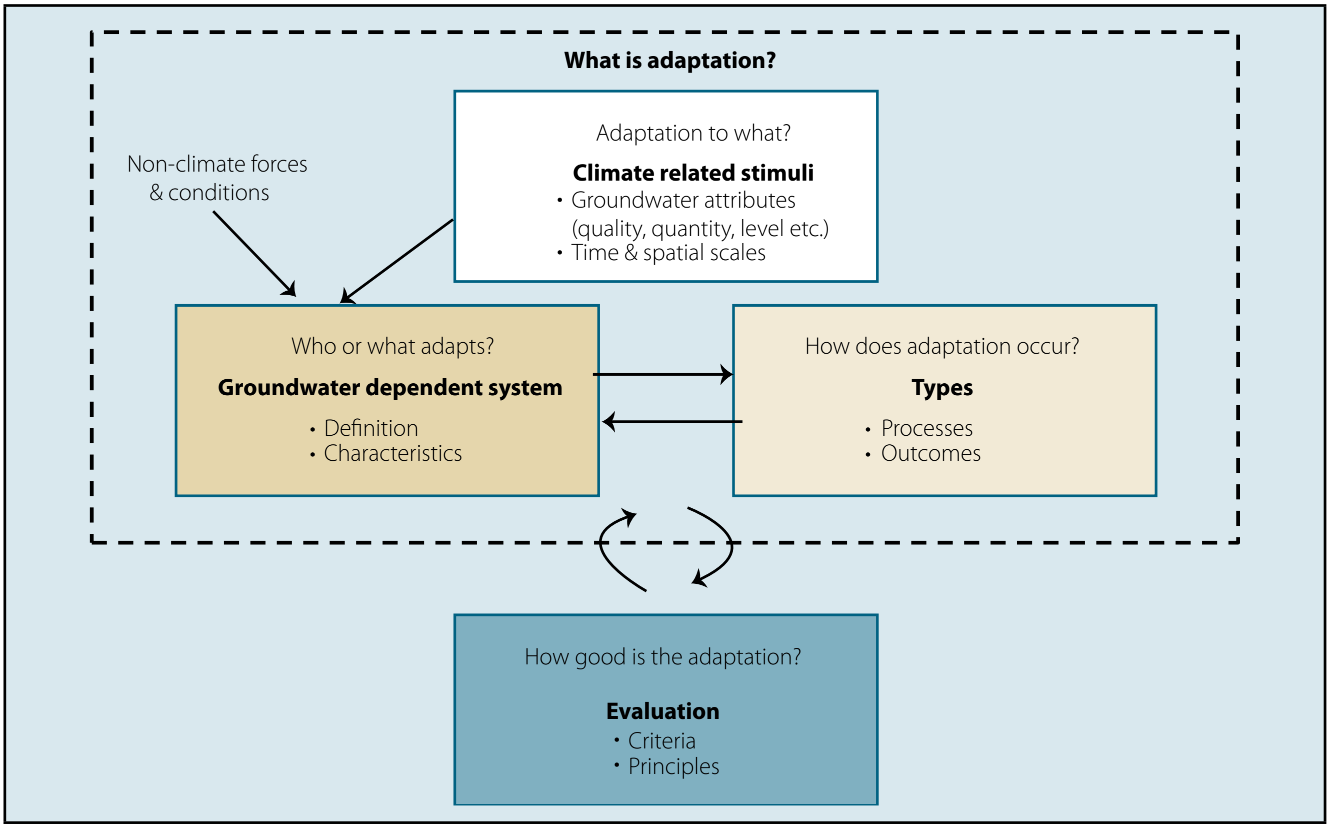
Figure 3.2 (from Smit et al., 2000) uses three primary questions to conceptualize climate adaptation: (1) adaptation to what, (2) who or what adapts and (3) how does that adaptation occur? Identification and/or development of adaptations should reflect an understanding of these three components. Prior to use or implementation, adaptations should also be evaluated to determine whether they are fit-for-purpose and cost-effective. Adaptations to climate change and variability must also complement or include adaptations to non-climate pressures or conditions that may affect the system.

Adaptation may occur as the result of planned action (e.g. Figure 3.2) or autonomously. Natural and human systems that are periodically challenged by climatic and hydrological extremes tend to adapt to minimize harm if challenged again in future. Planned adaptation is a pre-emptive response based on an assessment of future climate and hydrological risks.

Forms of adaptation

Burton (1996) developed a useful typology of climate change adaptation options (Figure 3.3), in which he

Figure 3.2: Conceptualization of Adaptation of a Groundwater Dependent System to Climate Change and Variability (redrawn from Smit et al., 2000)

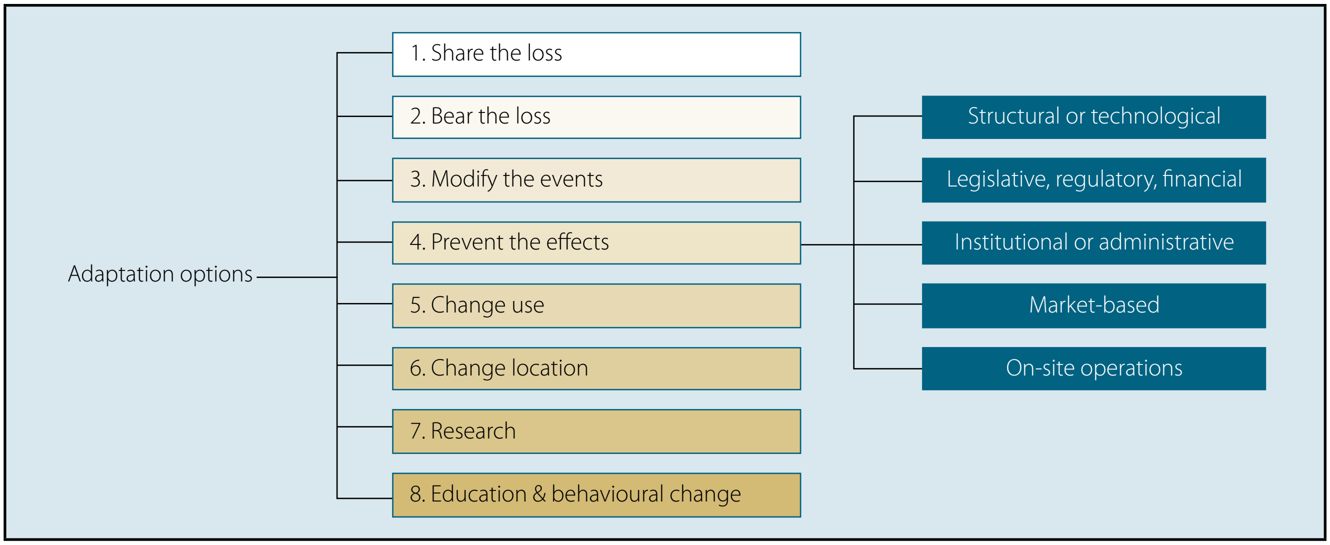


proposed eight broad types, which fall into five groups of risk responses, as follows:

Accept the risks – in which climate risks are accepted and no action is undertaken to change the exposure or (direct) sensitivity of the system to them. On those occasions when the system's coping range (Figure 3.1) is approached or exceeded, the associated losses are either borne (#2 in Figure 3.3) by those directly exposed or shared (#1 in Figure 3.3) among a broader group. Insurance is an example of the latter. Bearing the loss is a form of adaptation that would typically only apply when losses are either small in relation to the cost of other forms of adaptation or when they cannot be avoided (e.g. loss of ice cover in montane areas subject to increased temperature).

- Modify the likelihood of (or exposure to) a climate or related hazard (#3 in Figure 3.3) – in which actions are undertaken to reduce the frequency of events that take the system outside its coping range. In the example illustrated in Figure 3.1, this could include actions that increase groundwater recharge (e.g. vegetation cover change, artificial recharge) to maintain groundwater levels within the range accessible to the well or bore.
- Modify the consequences of (or sensitivity to) a climate or related hazard – in which actions are undertaken to extend the coping range of the system and prevent adverse impacts (#4 in Figure 3.3). The case from Figure 3.1 of extending the well to a greater depth to maintain access to water is one example of this type of adaptation. In addition to physical works and measures, this type of adaptation may include changes in institutional or regulatory arrangements and establishment of markets (Figure 3.3).
- Avoid the risk – by either changing the sensitivity (#5 in Figure 3.3) or exposure (#6 in Figure 3.3) of the system

Figure 3.3: Classification of Adaptation Options (redrawn from Burton, 1996)



to climate risks. For a groundwater dependent system, the former may involve reducing the reliance of the system on irrigation by, for example, moving from a perennial crop that must be irrigated every year to an annual one that is grown opportunistically, when water is available. The latter option may involve moving irrigated cropping to another location with a more reliable water supply.

- Build adaptive capacity – undertake research (#7 in Figure 3.3) to better understand the risks faced, the system's vulnerability to climate change and hydrological variability and/or improve or extend the range of adaptations. Education and behavioral change programs (#8 in Figure 3.3) could be developed and implemented to improve stakeholders' and communities' understanding of risks and management responses. Such campaigns might also empower groups to develop new adaptations or apply existing adaptations (across types #3–5 in Figure 3.3) more effectively or extensively.

All of these types are applicable to the groundwater vulnerability assessment framework. Acceptance of risk may be the adaptation choice in the first pass of the vulnerability assessment (Figure 3.1), in situations where there is low vulnerability or where there is no meaningful prospect of avoiding an impact (or consequence) should the adverse climate or hydrological state be realized. Other options would be considered in the second pass of the vulnerability assessment process.

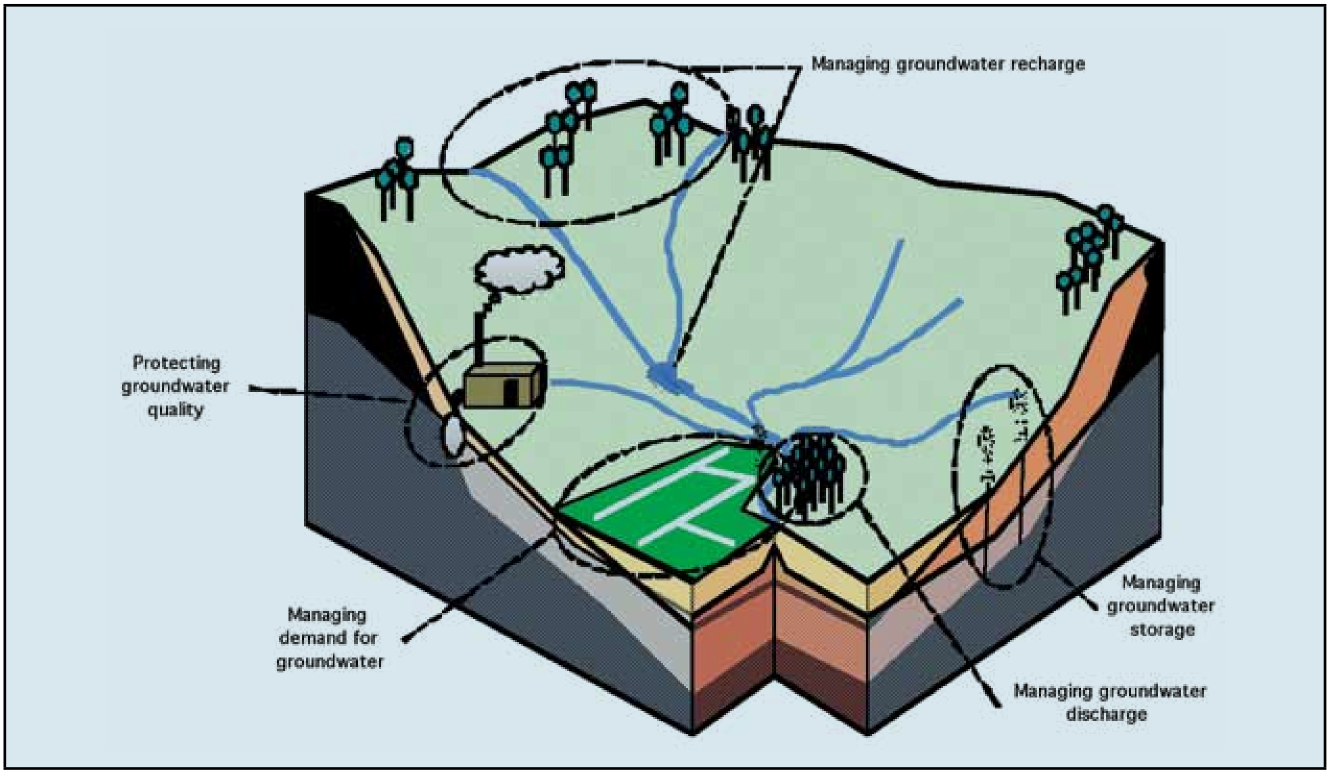
3.2 Adaptation options for risks to groundwater dependent systems from climate change and hydrological variability

This section contains a review of adaptation options for risks to groundwater dependent systems from climate change and hydrological variability. It is structured around the five groups of options discussed in the previous section, where they are appropriate and five main groundwater process themes (Figure 3.4):

- Managing groundwater recharge
- Management of groundwater storage
- Protection of groundwater quality
- Managing demand for groundwater
- Managing groundwater discharge

In most instances, 'accept the risk' options (#1 and #2 in Figure 3.3) are limited or need not be specified. These options are mostly likely to be considered where risk is low relative to the cost of adaptation or where other forms of adaptation are unlikely to be effective in mitigating risk.

Figure 3.4: Groundwater Adaptation Options, Based on Groundwater Processes and Location in the Landscape



Many of the options that fall within the 'building adaptive capacity' group are cross-cutting and at least partially apply to multiple themes. These are introduced in a separate section (below), preceding the discussion by groundwater themes. Applicable adaptive capacity adaptations are also listed for the various groundwater themes. Adaptation options in this section are relevant under situations in which climate change and hydrological variability reduce the security of groundwater supply and increase the vulnerability of the water dependent system. In contrast, Section 3.3 deals with adaptations to situations in which climate change is projected to result in groundwater recharge and/or discharge increasing to the point of adverse impact on a water dependent system.

3.2.1 Building adaptive capacity for groundwater management

Adaptive capacity building options are generally concerned with providing the necessary conditions for other forms of adaptation to be implemented successfully, rather than managing or avoiding climate or hydrological risks directly. They fall into several categories, as noted in section 3.1 (Table 3.1).

3.2.2 Managing groundwater recharge

Groundwater recharge areas may be managed to protect or enhance water resources and to maintain or improve water quality. While the latter is also covered in section 3.2.3, it is relevant here as activities in groundwater recharge areas that lead to groundwater contamination also reduce resource availability. Potential adaptations are outlined in Table 3.2.

3.2.3 Protecting groundwater quality

Climate change and hydrological variability may affect the quality of groundwater available for use in a groundwater dependent system. This is particularly true of groundwater

Table 3.1: Adaptation Options: Building Adaptive Capacity

Adaptation option group	Adaptations
Social capital These options are concerned with enabling communities to understand climate and hydrological risks and actively participate in management responses.	• Education and training – to improve community and stakeholder understanding of climate risks and their capacity to participate in management responses and/or generate, modify or apply adaptations. • Governance – devolve some level of responsibility for planning and management of groundwater to local communities to increase local 'ownership' of problems and responses • Sharing information – instigate processes for sharing of information regarding climate risks and responses within and between vulnerable communities.
Resource information Gathering and providing information on climate risks and the groundwater system being managed.	• Understanding climate – analysis of historical and palaeoclimate information to understand the natural drivers of climate variability and links between interannual to interdecadal climate modes (e.g. El Niño Southern Oscillation, Pacific Decadal Oscillation) and climate risks. Development of historical and synthetic climate datasets for climate impact studies. • Climate change projections – developing downscaled climate change projections for the area of interest. • Quantify the groundwater system – understand the scale and characteristics of the aquifer(s); recharge, transmission and discharge processes; water balance (including use); water quality etc. • Monitoring, evaluation and reporting – of the state of the groundwater resource, level of use, vulnerability to various threatening processes and effectiveness of climate and other adaptations.
Research & development Research and development activities to improve the effectiveness of adaptive responses to climate change and hydrological variability.	• Climate impact assessments – studies to better define the nature of projected climate change impacts on the groundwater system and the associated climate and hydrological risks. • Management of groundwater recharge – methods to enhance groundwater recharge and water availability. • Management of groundwater storage – technologies, water management and other practices to maximize groundwater storage capacity and resource availability. • Protection of water quality – technologies and management systems to enable treatment and reuse of contaminated water and avoid contamination of higher quality water by water of lesser quality. Protection of island and coastal aquifers from effects of sea level rise. • Managing demand for groundwater – technologies and management practices that: improve the efficiency of urban and agricultural uses of water; reduce water quality requirements of non-potable uses; or reduce the need for water. • Management of groundwater discharge – land management practices to reduce unwanted discharge of groundwater (especially) by non-indigenous woody vegetation. • Markets – improved arrangements for operation of markets for water and related environmental services. • Governance and institutional arrangements – improved methods for governance and stewardship of groundwater resources.
Governance & institutions Improving governance and institutional arrangements for groundwater resource management. Improved planning regimes for groundwater and associated human and natural systems.	• Conjunctive management of surface water and groundwater in rural areas. Integrated water cycle management (including various potable and non-potable sources in urban areas). • Multi-jurisdictional planning and resource management arrangements for large scale aquifer systems that cross jurisdictional boundaries. • Defining water allocations based on resource share rather than volume. • Set and regulate standards for (e.g.) groundwater resource and land use planning, water governance, environmental management, water quality, resource information, water use efficiency (in agricultural, industrial and urban settings).

(*continued on next page*)

Table 3.1: Adaptation Options: Building Adaptive Capacity *(continued)*

Adaptation option group	Adaptations
	• Set and enforce a cap on level of utilization of groundwater within a management unit. Cap should be based on the defined sustainable yield (accounting for robust understanding of climate risks and environmental water requirements of groundwater dependent ecosystems [GDEs]) unless there is to be planned mining of an historical groundwater resource. Cap and water allocations to be reviewed and reset periodically to account for changed management and development objectives and changes in climate and resource availability. • Human needs water reserve – secure allocation of groundwater to meet basic human needs in groundwater dependent communities. • Environmental water reserve – secure allocation of groundwater to meet requirements of GDEs. • Measurement and public reporting of groundwater use. • Drought response planning.
Markets Establishment and operation of markets for water and associated environmental services.	• Markets – establishment and operation of markets for and trading of water within a groundwater system. Market to determine the price for water. • Property rights – establish clear title and property rights to groundwater. • Include generation of recharge and surface water flows in water markets to enable payments by water users to owners and managers of land generating water of appropriate quality.

Table 3.2: Adaptation Options: Managing Groundwater Recharge

Adaptation option group	Adaptations

Modify exposure to climate risk (#3)	• Manage or reduce the level of woody vegetation cover to optimize groundwater recharge (while protecting ecological values and avoiding erosion etc.).
	• Managed aquifer recharge (MAR; or other forms of artificial recharge) in/near urban and rural settings to capture and use:
	  • urban storm water, including use of detention ponds and infiltration systems;
	  • treated wastewater from industrial facilities and urban wastewater treatment plants;
	  • overland flows – (e.g.) via capture in dams that are designed to leak and recharge water tables;
	  • river flows
	• Adjust land management practice in groundwater recharge areas to maximize water table recharge and reduce overland flows—for example through maintaining ground cover, contour banks, Keyline farming systems etc.
	• River regulation to maintain flows over recharge beds for alluvial aquifers.

Modify sensitivity to climate risk (#4)	*No options applicable*
Avoid risk (#5, #6)	• Land use planning controls that limit industrial forestry plantation development in key recharge areas. • Land use planning and environmental management controls to avoid development of industrial or other facilities, in key recharge areas, that pose high risk of aquifer contamination.

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Table 3.2: Adaptation Options: Managing Groundwater Recharge *(continued)*

Adaptation option group	Adaptations
Build adaptive capacity (#3-#5, #7)	• Land use planning and environmental management controls to regulate developments in key recharge areas that increase vulnerability of groundwater system. • Water allocation policy framework that incorporates impacts of land use on groundwater recharge and generation of surface flows. Land use changes with high water requirements required to purchase entitlement to intercept groundwater recharge or surface flow.

Note: # refers to the adaptation option type in Figure 3.3.

resources on small islands and coastal areas that are projected to be subject to sea level rise. It is also true where reduced security of supply leads water resource managers to include lower quality water in the supply stream (e.g. through MAR using storm water or treated waste water) or where increased pressure on groundwater resources leads to increased use and greater risk of contamination of a high quality aquifer by any overlying or underlying poorer quality aquifers. Adaptation options are outlined in Table 3.3.

Table 3.3: Adaptation Options: Protecting Groundwater Quality

Adaptation option group	Adaptations
Modify exposure to climate risk (#3)	• Regulate surface water and groundwater levels in rivers, lakes and surface water storages and shallow water table areas with potential acid sulfate soils to avoid activation and acid contamination of surface waters and groundwater. • Construct bore fields in coastal aquifers to drawdown the salt water aquifer and protect freshwater from incursion as sea levels rise. • Use MAR or other forms of artificial recharge of freshwater to coastal aquifers—to maintain heads in freshwater and protect aquifer from incursion by salt water as sea levels rise. • Manage utilization/drawdown of groundwater to avoid contamination of higher quality groundwater by poor quality water in overlying or underlying systems.
Modify sensitivity to climate risk (#4)	• Treatment of low quality water (e.g. desalination, filtration) to a standard appropriate for particular uses.
Avoid risk (#5, #6)	• Land use planning and environmental management controls to avoid development of industrial or other facilities that pose high risk of contaminating important water resource aquifers.
Build adaptive capacity (#3-#5, #7)	• Research to define sustainable yield and quality of aquifer systems—to ensure adequate water quality maintained. • Land use planning and environmental management controls to regulate developments that pose a high risk of contamination to aquifers. • Education and behavior change campaign, with appropriate monitoring and regulatory support, to emphasize avoidance of contamination of water resource aquifers industrial facilities, fuel or other chemical storages etc. • Research to develop water treatment processes that are less expensive and require less energy. • Develop water quality standards that can be applied to different uses. Supply water to meet these standards.

Note: # refers to the adaptation option type in Figure 3.3.

Table 3.4: Adaptation Options: Managing Groundwater Storages

Adaptation option group	Adaptations
Modify exposure to climate risk (#3)	- Increase storage capacity in aquifers—through hydrofracturing, dissolution (in karst systems) or pressurization of cavities. - Increase storage availability in aquifers prior to expected periods of high recharge. - MAR and other forms of artificial recharge to maximize use of available water and storage capacity in aquifers. - Re-inject water from mine dewatering operations into aquifer down gradient of mine (where of useful quality) rather than run to waste.
Modify sensitivity to climate risk (#4)	*No options applicable*
Avoid risk (#5, #6)	*No options applicable*
Build adaptive capacity (#3-#5, #7)	- Research and/or resource assessments to improve understanding of aquifer properties and define opportunities and management practices for more effective storage management. - Develop technical and analysis skills in groundwater resource managers to operate aquifers as groundwater storages. Develop monitoring infrastructure to support such management. - Develop seasonal and longer term forecasting/projection of groundwater resources based on well developed understanding of main climate drivers for aquifer. Base seasonal and long-term allocations on understandings of water availability.

Note: # refers to the adaptation option type in Figure 3.3.

3.2.4 Managing groundwater storages

While aquifers are recognized as underground water storages, they are rarely operated with the same level of precision and control as major surface water storages. Opportunities exist (Table 3.4) to manage groundwater storages more effectively, and reduce the vulnerability of systems that depend on them to climate change and hydrological variability.

3.2.5 Managing demand for groundwater

Climate change adaptations for water resources most frequently operate on demand management. In many cases, the adaptations for groundwater dependent and surface water dependent systems will be identical. Options are outlined in Table 3.5.

In areas where climate change reduces supply security for surface water resources, it is likely that there will be increased focus on utilization of groundwater resources *as an adaptation to climate change*. This will require greater attention to management of demand for groundwater and for conjunctive management with surface water. It may also be possible to use groundwater as a store for surplus surface water flows during periods of abundant supply for use during periods of surface water scarcity.

3.2.6 Management of groundwater discharge

Aquifer systems discharge water to the land surface, rivers, lakes, wetlands or to near or off-shore marine environments. Discharge, recharge and utilization are in a state of dynamic equilibrium, such that changes in recharge or utilization ultimately result in a change in discharge. In some settings, it is possible to increase resource availability (for use by human systems) by reducing groundwater discharge. Potential climate change adaptation options relating to management of groundwater discharge are outlined in Table 3.6.

Table 3.5: Adaptation Options: Managing Demand for Ground

Adaptation option group	Adaptations
Accept the risk (#1, #2)	• Crop insurance for drought-related crop or livestock production failures. • Welfare or related support payments to primary producers experiencing drought-related crop or livestock production failures
Modify exposure to climate risk (#3)	• Effectively cap artesian bores to reduce or eliminate wastage. • Use pipes or sealed channels to distribute water from groundwater pumps and/or artesian bores to point of use to reduce or eliminate waste from seepage or evaporation. • Use or improved use of seasonal forecasts and water allocation projections in crop selection and decisions on area to irrigate. • Maintain water reticulation systems (where they exist) to reduce leakage and wastage. Apply appropriate standards of construction and materials to water supply systems to reduce losses. • Develop system of water restrictions to apply to domestic and industrial consumption during periods of supply scarcity. • Secure and maintain environmental water provision for groundwater dependent ecosystems. • Substitute use of high quality groundwater for lower quality groundwater or water from other sources (e.g. treated waste water) as appropriate to the use. • Use MAR to 'bank' groundwater for use during periods of scarcity of surface water supplies.
Modify sensitivity to climate risk (#4)	• Measure use of groundwater. • Improve on-farm efficiency of water use—e.g. control deficit irrigation (where appropriate to crop), improved irrigation scheduling, use of more efficient application methods (i.e. sprays, drip irrigators or underground irrigation rather than flood, furrow or overhead sprinklers). • Select crops with lower water requirements and/or higher value per unit of water required. • Achieve balance of perennial horticulture (with high sensitivity to water shortage) and opportunistically irrigated annual crops in order to match water use with the projections of water resource availability. • Substitute irrigation production for dryland agriculture to the extent required by the level of irrigation supply.
Avoid risk (#5, #6)	• Land use planning to limit urban and/or agricultural development to levels consistent with current and projected water supply availability.
Build adaptive capacity (#3-#5, #7)	• Conjunctive management of surface water and groundwater in rural areas. Integrated water cycle management (including various potable and non-potable sources in urban areas). • Water allocation framework for groundwater use that limits allocations to sustainable yield (unless there is planned depletion of historical reserves). Water allocations to be reviewed and reset periodically to account for changed management and development objectives and changes in climate and resource availability • Multi-jurisdictional planning and resource management arrangements for large scale aquifer systems that cross jurisdictional boundaries. • Set and regulate standards for (e.g.) groundwater resource planning, water governance, environmental management, water quality, resource information, water use efficiency (in agricultural, industrial and urban settings). • Development and implementation of economic tools (for example pricing/charges/tariffs for groundwater within an aquifer system). Pricing to reflect demand and any costs of supply and treatment. Where appropriate, more complex economic markets could be established.

(*continued on next page*)

Table 3.5: Adaptation Options: Managing Demand for Ground *(continued)*

Adaptation option group	Adaptations
	• Defining water allocations based on resource share rather than volume. • Water resource managers to provide early advice to irrigators on water allocations. • Human needs water reserve—secure allocation of groundwater to meet basic human needs in groundwater dependent communities. • Environmental water reserve—secure allocation of groundwater to meet requirements of GDEs. • Measurement and public reporting of groundwater use. • Research to develop more water efficient irrigation and agricultural production systems and crops. • Education and behavior change campaign to increase adoption of existing (and any new) adaptations for agricultural water use efficiency. • Education and behavior change campaign to raise awareness of water conservation issues and practices and change attitudes and behaviors. • Community-level participation in water resource planning processes, especially for irrigation. • Stepped pricing structure for domestic and industrial water use—with price per unit volume increasing in multiple steps as consumption extends beyond basic needs.

Note: # refers to the adaptation option type in Figure 3.3.

Table 3.6: Adaptation Options: Managing Groundwater Discharge

Adaptation option group	Adaptations
Modify exposure to climate risk (#3)	*No options applicable*
Modify sensitivity to climate risk (#4)	*No options applicable*
Avoid risk (#5, #6)	• Avoid or limit establishment of industrial forestry plantations or other deep-rooted, high water use species in areas with shallow, fresh groundwater that is used for other purposes.
Build adaptive capacity (#3-#5, #7)	• Land use planning controls that enable restrictions on the extent to which high water use species are established in areas with shallow, fresh groundwater that is used for other purposes. • Market mechanisms that account for groundwater uptake by land uses (e.g. forestry plantations) in a consistent way with other direct uses of groundwater.

Note: # refers to the adaptation option type in Figure 3.3.

3.3 Managing for increased groundwater recharge

While it is the case that the latest climate change projections (IPCC, 2007) suggest a worsening of water security in many nations, this is not always the case. Kundzewicz et al. (2007; for surface water flows) and Döll and Florke (2005; for groundwater; Figure 2.2) present data that projects increase surface flows and groundwater recharge under some emissions scenarios. Areas projected to have increased recharge include some where water is currently in short supply (e.g. parts of the Sahel region of Africa, parts of the Arabian Peninsula, north-east China) and others (e.g. Siberia) where it is not.

Increased rainfall and recharge in some areas may, other factors being equal, lessen the vulnerability of groundwater dependent systems. However it is conceivable that in some locations, increased recharge associated with changes in climate and hydrological variability may make some aspect of such systems more vulnerable. Such circumstances include, for example, hydrogeological settings in which increased recharge results in the development of shallow water tables and salinization of land and water resources (such as has occurred in parts of southern Australia in response to the replacement of native woody vegetation with agricultural crops and pastures; NLWRA, 2001) or geological instability.

Potential options for adapting to increased groundwater recharge are outlined in Table 3.7.

3.4 Examples of adaptation to climate change and hydrological variability from developing countries

3.4.1 Managed aquifer recharge

Managed aquifer recharge (MAR) involves building infrastructure and/or modifying the landscape to intentionally enhance groundwater recharge. It forms one of the 'managing aquifer recharge' adaptation responses listed in Table 3.2 and is increasingly being considered as an option for improving the security and quality of water supplies in areas where they are scarce (Gale, 2005).

MAR is among the most significant adaptation opportunities for developing countries seeking to reduce vulnerability to climate change and hydrological variability. It has several potential benefits, including: storing water for future use, stabilizing or recovering groundwater levels in over-exploited aquifers, reducing evaporative losses, managing saline intrusion or land subsidence, and enabling reuse of waste or storm water.

Implementation of MAR requires suitable groundwater storage opportunities. Falling water levels or pressures in aquifers in many regions throughout the world are creating such opportunities, either as unsaturated conditions in unconfined aquifers or as a pressure reduction in confined aquifers. However, MAR is not a remedy for water scarcity in all areas. Aquifer conditions must be appropriate and suitable water sources (e.g. excess wet season surface water flows or treated waste water) are also required. MAR

Table 3.7: Adaptation Options: Managing Increased Groundwater Recharge

Adaptation option group	Adaptations
Modify exposure to climate risk (#3)	• Change land use or management to increase woody or other higher water use vegetation cover. • Establish deep rooted vegetation in areas subject to instability if seasonally water-logged. • Construct surface or sub-surface drainage in discharges to intercept groundwater and drain to appropriate location (e.g. stream for fresh water, evaporation basin for saline water). • Groundwater pumping to hold water table at a safe depth in the vicinity higher value agricultural or environmental assets and population centers. • Increase use of groundwater for irrigation or other purposes.
Modify sensitivity to climate risk (#4)	• Establish high water use vegetation in groundwater discharge areas (that are adapted to soil and water salinity) to increase groundwater discharge. • Establish salt tolerant vegetation (with commercial use in grazing or cropping) in salinized, shallow water table areas.
Avoid risk (#5, #6)	*No options available*
Build adaptive capacity (#3-#5, #7)	• Research and development to introduce farming and other management systems that reduce the vulnerability of natural and human systems to the consequences of increased recharge.

Note: # refers to the adaptation option type in Figure 3.3.

potential should be determined in any particular country or region before activities commence.

MAR may not succeed as a stand-alone adaptation to scarcity of groundwater supply. Its implementation should also be accompanied by demand management (Table 3.5) and capacity building (Table 3.1) measures. Without these MAR may fail, particularly where aquifers are overexploited or where poor selection of the MAR site and/or type occurs due to lack of appropriate knowledge (Dillon, pers. comm., 2008).

MAR methods may be grouped into the following broad approaches (Figure 3.5):

- Spreading methods – such as infiltration ponds, soil-aquifer treatment, in which overland flows are dispersed to encourage groundwater recharge;
- In-channel modifications – such as percolation ponds, sand storage dams, underground dams, leaky dams and recharge releases, in which direct river channel modifications are made to increase recharge;
- Well, shaft and borehole recharge – in which infrastructure are developed to pump water to an aquifer to recharge it and then either withdraw it at the same or a nearby location (e.g. aquifer storage and recovery, ASR);
- Induced bank infiltration – in which groundwater is withdrawn at one location to create or enhance a hydraulic gradient that will lead to increased recharge (e.g. bank filtration, dune filtration)
- Rainwater harvesting – in which rainfall onto hard surfaces (e.g. building roofs, paved car parks) is captured in above or below ground tanks and then allowed to slowly infiltrate into soil.

There are several common operational issues experienced by MAR schemes (Gale, 2005). These include: clogging of wells, stability of infrastructure under operating conditions, protection of groundwater quality, operation and management of the scheme, ownership of the stored water, monitoring, loss of infiltrated/injected water, policy and cultural acceptability and related stakeholder communications. Successful operation requires appropriate training for operators, access to successful demonstrations of the technologies being deployed and sound and integrated management of water resources[6].

Detailed planning and assessment are required to determine whether MAR is a viable adaptation option. This may be carried out a national and watershed scale. Three fundamental planning steps should be considered:

- Water availability – assess the availability and quality of excess wet season surface water flows or other potential sources. The frequency and volume of availability of suitable water must be assessed for each planning region, as must the influence of natural climate variability and projected human-induced change.
- Evaluate the hydrogeological suitability of the MAR site or region – which largely depends on ease of injecting and recovering the water, the aquifer storage capacity and the aquifer's resistance to clogging.
- Feasibility - the costs, benefit and feasibility of constructing and operating a MAR scheme, including those associated with transporting the recovered MAR water to demand centers needs to be determined.

MAR will not be appropriate in some hydrogeological settings and for some classes of water. Various MAR options exist and are appropriate to parts of at least some World Bank regions.

MAR example: sand dams in Kenya

Sand dams are made by constructing a wall across a riverbed, which slows flash floods/ephemeral flow and allows coarser sediment to settle out and accumulate behind the dam wall. The sedimentation creates a shallow artificial aquifer which is recharged both laterally and vertically by stream flow (Gale, 2005).

Since 1995, over 400 sand dams have been constructed in the Kitui District of Kenya, supported by the SASOL

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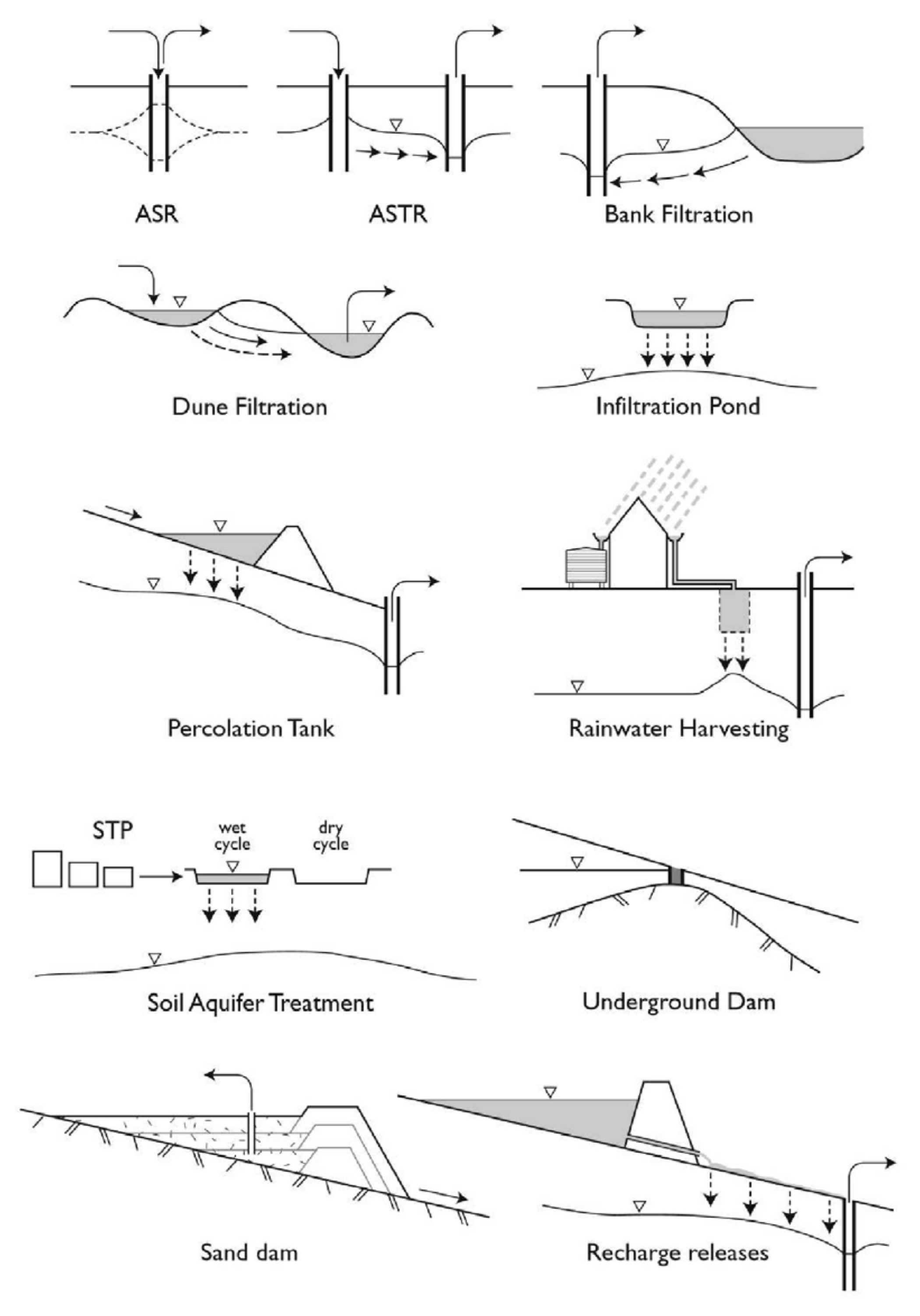
[6] An IAH (International Association of Hydrogeologists) Commission on MAR are currently working with UNESCO to provide information and education resources about MAR, see: www.iah.org/recharge/.

Figure 3.5: Examples of Managed Aquifer Recharge (MAR) Approaches



ASR: aquifer storage and recovery; ASTR: aquifer storage, treatment and recovery, STP: sewage treatment plant. Source: Peter Dillon (pers. comm., 2008)

Foundation (Figure 3.6; Foster and Tuinhof, 2004). Each of these dams provides at least 2,000 m^3 of storage and has been constructed by local communities using locally available material. The benefits identified through this program include: water supplies more readily available in the dry season, enhanced food security during drought periods, and less travel time to obtain water supply.

Sand dams are not appropriate for all locations. They require unweathered and relatively impermeable bedrock at shallow depth; the dominant rock formation in the area should weather to coarse, sandy sediments; sufficient overflow is required for fine sediments to be washed away; and risk of buildup of soil and groundwater salinity needs to be low. Cooperative effort, ownership and ongoing maintenance by the local community are also necessary for the success of these schemes (Foster and Tuinhof, 2004).

3.4.2 Groundwater protection: adaptations and challenges for a low atoll

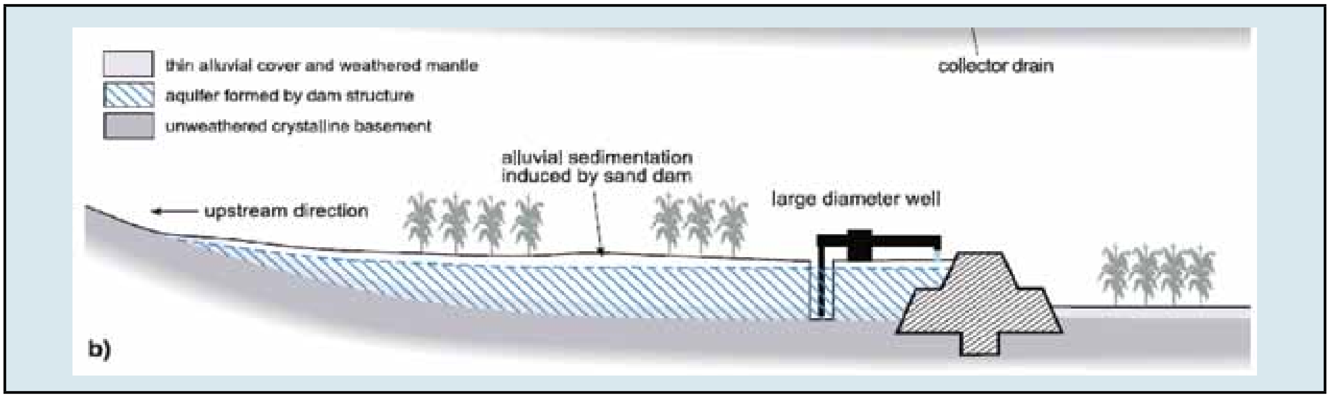
Thin lenses of fresh groundwater floating over seawater comprise the major source of water supply in many atolls. Limited land area, permeable soils and limited vertical relief constrain surface water storage and availability (White et al, 2007). Fresh groundwaters in these environments are becoming increasingly vulnerable, threatened by sea level rise, drought, increasing populations and land use change.

White et al. (2007) examined the impact of both ENSO-related droughts and human influences on freshwater availability, and assessed potential adaptation strategies to protect water resources and reduce risks for the densely populated central Pacific atoll, Tarawa, Republic of Kiribati. Whilst focused on an atoll environment, the findings from this work are applicable to many island and coastal regions, and the principle of recharge zone protection is common for all areas where fresh groundwater is available.

Water supply for Tarawa's reticulated system is extracted from freshwater lenses in groundwater reserves. During drought periods, almost all rainwater tanks are exhausted, the thickness of the fresh groundwater lens decreases, many domestic wells become saline and saline groundwater causes the death or severe dieback of mature bread-fruit trees. However, provided pumping occurs at a sustainable rate, large freshwater lenses have historically survived through extended droughts with only moderate increases in salinity.

In order to preserve the freshwater resource and supply for drought periods in Tarawa, it is critical to reduce contamination risk to groundwater. Whilst traditional practices in low-density populations have evolved to minimize contamination risk—for example, defecation on beaches down-gradient from recharge areas and keeping pigs in pens in groundwater discharge zones—these are often in conflict with contemporary land use trends and behavioral patterns.

Figure 3.6: Cross section of Sand Dam Structure (from Foster and Tuinhof, 2004)



In particular, the keeping of pigs and market gardens in groundwater source areas provide contamination problems for Tarawa.

Historical adaptation measures have been applied with limited success. Installation of reverse osmosis desalination units during previous drought periods failed due to intermittent power supplies, lack of training, and maintenance and operational costs (estimated at 16 times that of groundwater extraction). There has been mixed success for declaring privately owned land in groundwater recharge areas as water reserves with restricted land uses; often the restricted rights of affected landowners has resulted in conflict. Poor access to information regarding available water storage and the impacts of climate variations has also made it difficult to establish water policies and legislation.

Proposed future adaptation strategies for Tarawa broadly fall under three themes: capacity strengthening, demand management and refurbishment of infrastructure and protection and supplementation of freshwater resources. Specifically, these include:

- Establishing a sound institutional basis for the management of water and sanitation;
- Improving community participation in water and related land management planning to reduce conflicts;
- Increasing capacity to analyze and predict extreme water events (especially droughts);
- Improving knowledge of available water resources, including their quality and demand upon them.
- Improving water conservation and demand management strategies and reduce leakage from water supply infrastructure;
- Protecting groundwater source areas from contamination.

White et al. (2007) conclude that improving and sharing knowledge about climate and water resources is an essential element of adaptation and that this knowledge must be communicated in a way that is consistent with traditional oral forms of knowledge transfer. They also highlight the need for investment in regional solutions, local engagement and long-term partnerships.

3.5 Discussion

3.5.1 Avoiding adaptation decision errors

Decisions to apply climate change adaptations are made in an uncertain environment. Even so, decision makers need to consider the risks associated with the future being different to that projected or to the adaptation options not performing as well as expected (Willows and Connell, 2003). Three broad types of adaptation error are recognized:

- Underadaptation – which is likely to result from situations in which climate change should have been an essential component of a decision, but was either ignored or given less weight relative to other factors than it should have. Such situations are likely to result in insufficient weight being given to climate change adaptation
- Overadaptation – which results from the inverse of conditions associated with under-adaptation. The importance of climate change risks is overstated relative to other factors and greater emphasis than was necessary is placed on adaptation.
- Maladaptation – in which actions are taken which reduce the options or ability of decision makers to manage the impacts of climate change.

Given the uncertain decision-making environment for climate change adaptation, it is necessary to balance the risks of under and over-adaptation. In the first instance, 'no regrets' adaptations, which make sense even in the absence of experienced climatic change, should be deployed. Beyond that, the level of investment in adaptation will depend on the resources available and the severity of consequences and likelihood of various climate change impacts. Where potential impacts are severe and resources are available, the risk and implications of underadaptation may be too great to bear.

The concept of maladaptation should also be extended to include actions that either conflict with other social, economic, resource management or environmental objectives or add further pressure to the global climate system by significantly increasing greenhouse gas emissions. Examples could include:

- clearing native vegetation to increase recharge to aquifers – this would result in emissions of greenhouse gases and loss of biodiversity and could lead to erosion and increased flash-flood risk;
- increasing water availability through treatment of low quality water using processes that expensive and energy intensive processes which will be operated using coal-fired power stations;
- introduction of market-based measures for water resource management that impoverish, or further impoverish small irrigation producers.

3.5.2 Evaluation of adaptation options

The need to avoid the adaptation decision errors described in the previous section suggests some form of evaluation process prior to implementation. Drawing on work carried out for the IPCC, Dolan et al. (2001) identified several possibilities, including benefit-cost analysis, cost-effectiveness analysis, risk benefit analysis, multi-objective analysis and multiple criteria evaluation. They also applied a Multiple Criteria Evaluation (MCE) or Multi-Criteria Analysis (MCA) to evaluate a set of adaptation options applicable to Canadian agriculture. The criteria used included:

- effectiveness
- economic efficiency
- flexibility
- institutional compatibility
- farmer implementability
- independent benefits[7]

The criteria appear to be broadly suited to the evaluation of adaptations in other economic or social sectors, including groundwater resource management. However, 'farmer implementability' would need to be amended to the more generic 'implementability'.

The evaluation anticipated by the vulnerability assessment process (described in the larger report) is against criteria framed around management and development (or other) objectives for the groundwater system. It is anticipated that these would have social, economic and environmental dimensions. Effectiveness is determined by a re-run of the overall risk assessment to determine if there is any change in vulnerability with the suite of applicable adaptations. The latter are those which are practically implementable and either institutionally compatible or not outside the bounds of realistic institutional reform. Economic efficiency would most likely be incorporated within an assessment against economic objectives. Flexibility is relevant, but is not explicitly considered in the evaluation. Adaptation options would only be selected if they could be 'adapted' to local circumstances.

3.5.3 Barriers to introduction of adaptations

Many of the adaptations described in this section are based on experiences of developed nations with experience of climatic and hydrological variability and with robust institutional arrangements for water resource management. Under current conditions, many of the adaptation options may not satisfy criteria such as cost, implementability and institutional compatibility (Dolan et al., 2001) for World Bank client countries. Successful introduction would require external technical and financial support, as well as institutional strengthening and policy reform. The challenges in establishing an appropriate institutional setting for introducing many of the 'adaptive capacity' options should not be underestimated.

3.5.4 Economic considerations

Groundwater management is fundamental to the sustainability of water resources and there are strong environmental, economic and social reasons that justify government investment in groundwater management and adaptation to climate change. Not least of these is the ability for governments to continue to provide water for basic human needs and groundwater dependent industries such as agriculture.

Across most countries in the world, groundwater is currently supplied for free, or at a minimal fee. Without an income stream, investment by governments in groundwater management is not profitable and is thus often poorly

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[7] Benefits not relating to the contribution to avoiding or reducing risks associated with climate change.

addressed. Successful management and implementation of adaptation options will only occur if there is adequate financial support. Adaptation options must therefore be assessed against economic objectives that factor any initial and ongoing costs, and available means for financing these.

All adaptation options cost money: there is no free or cheap generic solution that will resolve the current and future pressures on groundwater resources globally. But economically feasible options do exist. In developing nations, low cost low technology solutions are likely to be more successful. In some cases, the costs and benefits of an adaptation option may warrant introducing fees/charges for groundwater use, so that an appropriate level of cost recovery is met.

The economic feasibility of an adaptation option, or suite of options, will depend on a number of factors:

- *Cost of start-up* – costs associated with the initial phases of implementing an adaptation option, for example, building materials and labor to build a managed aquifer recharge scheme, or human resources, software and computer storage for establishing a groundwater database. The cost of start-up will depend on the adaptation type, scale, where materials are sourced from, local access to expertise, the amount of in-kind contributions etc.
- *Ongoing costs* – due to (for example) monitoring and maintenance requirements.
- *Revenue* – whether or not the options have a source of income, such as fees for water usage, to enable some cost recovery.
- *Local economic conditions* – this will affect costs for materials and labor, and the degree to which a community or country is able to fund the option themselves (versus the need to loan money from elsewhere).
- *External financers* – the availability of financial contributions and/or loans from external sources, and the conditions under which these finances are provided (time frame required for pay back, interest rate levels etc).

The diverse range of managed aquifer recharge (MAR) schemes (see Section 3.4.1) illustrates how the economics of different adaptation options can vary considerably. Low technology schemes such as surface spreading basins and sand dams are less expensive (about US$10 to US$50 per ML, ignoring pipeline costs) than, for example, borehole injection methods (in the order of US$100 to US$1,000 per ML). Consequently borehole injection methods are often less viable, particularly for agricultural purposes, although in some areas may be suitable for urban and domestic water use. This provides an example where the economic feasibility is driven not only by cost, but also other considerations such as the scale of the scheme and the end-user of the water resource.

4. EXAMPLES OF ADAPTATION MEASURES

4.1 Introduction

Case studies of adaptation in groundwater resource management to climate change and hydrological variability in the United Kingdom, USA and Australia have been prepared. They illustrate approaches to adaptation to climate risks for groundwater dependent systems in contrasting situations, but from countries with relatively mature information bases and institutional arrangements for water resource management. They provide a useful guide to approaches to adaptation to climate change and hydrological variability and also illustrate some of the challenges involved.

The case studies demonstrate a wide range of adaptations across many of the types described in sections 3.1 and 3.2. The adaptations are primarily in response to water scarcity and to minimize risks to water quality. Measures identified or implemented in the case studies include:

- *Building adaptive capacity* – through understanding the system's exposure and sensitivity to climate risks, conjunctive water resource planning, establishment of markets for water, establishing and applying standards for water use measurement, establishing goals for sustainable levels of water use; increasing end-user engagement in water resource planning and management, separate management of water for consumptive and environmental uses and community education-behavior change campaigns.
- *Modify exposure to risks from climate change and hydrological variability* – through supply augmentation and diversification, conjunctive planning and use of groundwater and surface water resources, managed aquifer recharge, deepening groundwater utilization bores, protection of source water quality, environmental water provision for groundwater dependent ecosystems and setting and enforcing caps on water use.
- *Modify sensitivity to climate change and hydrological variability* – through improved soil management to increase rainfall infiltration and reduce reliance on irrigation, improve irrigation scheduling and application techniques, urban water demand management (e.g. adjustment of building codes, implementing domestic water conservation measures, water restrictions), adjusting livestock numbers to balance demand for and availability of fodder from irrigated pastures, and land use planning controls to cap local population growth.
- *Avoiding risk* – including through adjustment of agricultural enterprises to reduce requirement for irrigation, balancing grazing livestock numbers to capacity to provide fodder from limited irrigation and sourcing alternative water supplies that are less or not sensitive to climate (e.g. desalination or inter-basin transfer).

4.2 Case study comparison

Steps from the vulnerability assessment framework (described in the larger report) have been used to compare the adaptation case studies and to illustrate commonalities and differences between case study approaches and the vulnerability assessment framework. It is important to note that the methods used in each of the case studies were not based on the vulnerability assessment framework and thus some elements of the framework are not applicable.

4.2.1 Establishing the context

Table 4.1 outlines the context for the four adaptation case studies, based broadly on the first step of the vulnerability assessment framework. Additional contextual information is provided in the case study summaries (Sections 4.3, 4.4 and 4.5).

The water supply systems in each of the case studies are critically dependent on groundwater and all have been exposed to drought/climate change in recent years. Combined with growing demand and/or competition for groundwater from urban and/or rural users, water resource managers in each of the case studies face a declining or potentially declining water supply. In some cases water quality is also under threat. An increasing value on, and legislative requirements to protect, the environment have also influenced the way in which groundwater resources are managed.

Table 4.1: Context for the Four Adaptation Case Studies

	Case study			
	UK – East Anglia	**USA – Oro Valley**	**Australia – Gnangara Mound**	**Australia - Hawkesdale**
Location	Eastern England	South west USA	Western Australia	South eastern Australia
Planning time-frame	6-yearly cycle Water allocated on a 12 year timeframe	10-yearly cycle Water allocated on a 100 year timeframe	2030 and beyond	Considers climate change impacts at 2030 and 2070
Groundwater system	Chalk limestone & Crag (gravels, sands, silts & clays) aquifers Groundwater fully allocated. Used for irrigation, residential, commercial & environment Temperate climate	Tertiary sedimentary (sand, gravel, conglomerate) aquifer Groundwater over-allocated. Sole source for town water supply. Semi-arid climate System is very sensitive to changes in rainfall	Superficial (sand) water table aquifer, plus deeper confined aquifers Groundwater over-allocated. Used for urban water supply, irrigation, industry & the environment. Mediterranean climate Groundwater supports wetland & cave ecosystems	Port Campbell limestone, Newer volcanic basalt, plus deeper confined aquifers Groundwater is used for stock & domestic, dairy and irrigation. Temperate climate Insufficient data to know if the system is fully allocated or not Plantation forestry in the area
Stakeholders	Irrigators, food industry, Environment Agency, residents, Government	Residents, Oro Valley Water Utility, Government	Residents, Government, farmers, tourism and other industries	Irrigators, dairy & forestry industries, stock and domestic users, Government
Key objectives	To meet the future water needs of abstractors without damaging the environment.	To meet future water needs of the Oro Valley township. To balance groundwater use with groundwater recharge	To meet future water demand To protect groundwater dependent ecosystems	To ensure groundwater extraction falls within the 'sustainable yield' of the aquifer^{+}
Success criteria (example)	Meet water quality guideline criteria	Sustainability thresholds for groundwater levels	Thresholds for wetland water levels	NA
Climate change scenarios	Historical, current	Drought conditions	Historical, current	Historical, current, 2030 best/worst case, 2070 best/worst case
Drivers for adaptation	Water use demand Changes in the value society places on the environment European Water Framework Directive Recent drought	Persistent drought conditions Population growth Declining groundwater levels & reduced well production capacity	Population growth and increased water demand Declining groundwater levels Recent drought Environmental values	Drought State Government policy Increasing demand

The sustainable yield is the renewable part of the groundwater resource, identified after making allowance for acceptable impacts on users, the surface environment and the resource itself.

With the exception of the Hawkesdale case study, future climate change scenarios are not explicitly included in the water resource planning process. Instead, historical climate and recent drought conditions have been used, assuming that the latter represents a conservative worst case scenario for the future. There are potential limitations to this approach, as discussed in Section 4.2.6.

4.2.2 Identifying and analyzing risk

Table 4.2 summarizes the climate risks identified in each of the case studies and how these risks have been analyzed. Across all case studies, the most significant climate hazards are reduced rainfall and increased frequency of drought. Hazards for the groundwater system include reduced recharge, groundwater contamination and an increased

Table 4.2: Case Study Overview – Identifying and Analyzing Risk

	Case study			
	UK – East Anglia	**USA – Oro Valley**	**Australia – Gnangara Mound**	**Australia – Hawkesdale**
Climate hazards	Warmer wetter winters Warmer drier summers Increased frequency of drought and flood	Reduced rainfall Increase in temperature More severe drought	Reduced rainfall Increase in temperature Increased frequency of drought	Reduced rainfall Increased temperature Increased frequency of drought
Climate related hazards for the groundwater system	Delay in the start of the recharge season Shorter recharge season Increased vegetation water use Increased water demand for the public, irrigators and the environment Reduced water quality	Reduced groundwater recharge Increased demand for groundwater	Reduced groundwater recharge Increased demand for groundwater Reduced water supply to groundwater dependent ecosystems	Reduced recharge Increased demand for groundwater, due to a shift from dryland to irrigated agriculture
Pre-existing climate risk controls	Time-limited abstraction licences Cessation conditions when groundwater or river levels drop below a set threshold.	Further development of groundwater resource	Limits on groundwater allocation Restrictions on groundwater pumping	Further development of groundwater resource
Assess consequences and likelihood of potential climate impacts	Potential consequences are identified (e.g. inadequate water supply for irrigation, domestic use and the environment). However, no formal assessment has been made.	Assessment of sustainable extraction under drought conditions has been made. Future climate change scenarios were not included.	Aware of potential consequences for water supply system and ecosystems. Likelihood of consequences is not documented.	Likelihood of reduced groundwater recharge modeled for each of the climate change scenarios. No assessment of other consequences.
Risk rating	No risk rating	No risk rating	No risk rating	No risk rating

demand for water. Each of these is affected by climate, but also by other factors such as land use and population growth.

Pre-existing climate risk controls comprised either (1) further development of the groundwater resource to meet water needs, or (2) limits on groundwater allocation and abstraction to ensure groundwater levels are maintained, particularly where these sustain important ecosystems or provide a critical potable water supply. In all case studies, it was acknowledged that these measures alone did not form an adequate response to climatic influences and other pressures on the system, particularly in the Oro Valley and Gnangara Mound case studies where declining groundwater level trends occur.

None of the case studies have documented any analysis of climate risk. Whilst water resource managers are aware and are acting upon the consequences of potential climate risks (e.g. inability to meet water needs, decline in ecosystem health etc), there is no formal documentation of the likelihood of these consequences occurring.

4.2.3 Evaluating and treating risks

Table 4.3 outlines if and how the case studies have documented processes for evaluating and treating climate risk.

The case studies do not document any process for prioritizing climate risks. Uncertainties associated with climate risks are also not addressed, with the exception of the Hawkesdale GMA. In this case probability distributions of rainfall and groundwater recharge were modeled to understand the uncertainties in future rainfall and groundwater recharge (see the larger report for more details).

The case studies have identified a number of adaptation options, across the types previously described in Section 4.1. The assessment of these adaptations has not been documented, but is likely to have included factors such as the ability to meet desired environmental, social and economic outcomes, despite water scarce conditions; ability to meet legislative and regulatory requirements; financial viability; acceptable impacts on local economy and stakeholders, etc.

Case studies have not tested identified adaptations against future climate change scenarios, although have considered existing climate (including drought) conditions. If future climate change scenarios include conditions worse than the recent drought, this approach could result in underadaptation. Each of the case studies acknowledge that in the face of future climate change additional adaptations may be required if water resource managers are to meet their key objectives. Additional options raised include: water trading, better conjunctive use of surface water and groundwater, relaxing the development of local groundwater resources and relying more on alternative renewable water resources, and expanding existing approaches such as managed aquifer recharge.

4.2.4 Stakeholder engagement

Stakeholder engagement forms an important component for all of the case studies. The development and engagement of farmer groups in East Anglia provided a powerful tool for educating community and implementing adaptation options. It also created an environment for innovation in water use efficiency, and a communication channel for irrigators to be informed so that they in turn can make sound investment decisions. In the Oro Valley, successful stakeholder engagement is critical for the implementation of their water conservation program.

In the Gnangara Mound, stakeholders are currently being engaged in the development of a sustainability strategy. This strategy is taking a whole of government approach, involving and liaising with diverse groups, including land use planning, water resources, infrastructure, and biodiversity. This provides an opportunity to manage water resources in a holistic way.

In the Hawkesdale GMA, meetings with stakeholders have been used to discuss possible climate change scenarios and impacts, and the likely implications for water allocation and planning. This assists stakeholders to understand what the future may be like and how they as individuals will need to adapt. It also provides an opportunity to address stakeholder concerns, reducing the likelihood of appeals against allocation decisions.

Table 4.3: Case Study Overview – Evaluating and Treating Risk

	Case study			
	UK – East Anglia	USA – Oro Valley	Australia – Gnangara Mound	Australia - Hawkesdale
Prioritize risks and assess uncertainty	NA	NA	NA	Uncertainty captured in recharge modeling but no formal prioritization of risk
Identify adaptation options	Changes to abstraction licensing system Development of water abstractor groups Investment in more efficient irrigation technologies Installation of on-farm reservoirs Changes to land management above aquifers	Further groundwater development Water conservation Enhanced aquifer recharge Import surface water Reclaimed water use	Supplemental water for wetlands Re-hydrate cave systems Limit groundwater abstraction Alternate water sources (wastewater, desalinated sea water) Enhance recharge via MAR and land use change Demand management Sustainability strategy	Further development of groundwater resources, including deeper confined aquifers Groundwater use not currently included in policy (e.g. plantations) to be incorporated. Groundwater allocation limits Manage land use and its impacts on recharge
Assess adaptation options	Not documented	Not documented	Not documented	Not documented
Plan and implement adaptation options	Options have been implemented	Some options have been implemented	Some options have been implemented or started to be implemented	With exception of allocation limits, options have not been implemented

4.2.5 Monitoring and review

Groundwater levels and chemistry are the most common monitoring methods for assessing the impacts of climate and other pressures on the groundwater resource. In the Gnangara Mound and East Anglia case studies, measures for surface water (e.g. levels) and ecological health are also included. This allows conjunctive management of both surface water and groundwater resources.

Currently there is very limited monitoring of groundwater in the Hawkesdale Groundwater Management Area, and this inhibits the understanding of the resource and the impacts of any change. Modeling approaches have been used to better understand the likely impacts here and monitoring bores have been recommended so real changes can be observed in the future. In the Oro Valley, groundwater is the only source of potable water supply and consequently levels are closely monitored to ensure security and reliability of supply.

In each of the case studies, water resource managers undertake periodic reviews of available data, including measurements of both the groundwater system (e.g. levels) and external pressures on the system (e.g. climate, population growth, metered groundwater use). Review of these data may be used to better understand the system and to assess the success of current and/or need for further adaptation. Where existing monitoring data cannot be used to measure established success criteria, additional monitoring may needed.

4.2.6 Observed success factors and barriers for adaptation

The case studies provide useful insights to both the success factors and barriers for implementation of adaptation options. Success factors identified include:

- *A multi-faceted approach* – ensures that outcomes are not reliant on a single or small group of measures. Incorporating ways to both enhance supply and reduce demand is more effective than looking at either of these approaches in isolation. Capacity building is also a vital component of any multi-faceted approach.
- *Collective action* – to be most effective, adaptation measures need to be supported at a range of levels (e.g. local, region, state) and across different groups (government, community, industry etc). This ensures that decisions are based on a broad knowledge base and that the adaptation approach is consistent with everyone working towards common objectives. Collective action also provides a means for sharing risk.
- *Strong hierarchy of values* – clear objectives and a strong values hierarchy are required to determine an appropriate response for restricting or supplementing resources that are put under pressure by climate change.
- *Adaptations with multiple benefits* – provides additional justification for investment and encourage stakeholder buy in.
- *Adequate capacity* – the availability of appropriate skills, knowledge and time is required to make sound decisions and to implement adaptation options. It is also important that local capacity is available (either currently or through training and development) for the ongoing implementation and maintenance of any adaptation option.

Barriers for successful adaptation comprise factors that prevent adoption, or that result in adaptation decision errors. Factors preventing adoption include:

- *Costs* – inability to justify the level of investment required to implement adaptation, due to lack of confidence in the benefits of adaptation or inadequate supply of funds.
- *Behaviors and attitudes* – community expectation regarding the quantity of water that will be available for their use in the future is a significant driver for water demand and a barrier for successful implementation of water conservation measures. It is difficult for people to change their perceptions and behaviors, and to accept that things in the future will be different to the past. Effective stakeholder engagement is able to mitigate some of these problems.
- *Uncertainty* – there are a number of uncertainties that impede investment in adaptation options, particularly large capital investments that require confidence in the future availability of water, future demand, and the economic environment. It is therefore important to incorporate uncertainty into the decision making process.

Factors that may contribute to adaptation decision errors are:

- *Lack of knowledge* – poor understanding of the significant drivers for current and future change in a groundwater system, including climate change, population growth, cultural, political and economic contexts etc can lead to misinformed decisions. The first step to identify adaptation options should be to establish the context including identification of all the significant drivers.
- *Inadequate scenario planning for the future* – in three of the four case studies, projected climate change was not explicitly considered in the development of adaptation options. Instead the focus was on meeting water demand under recent drought conditions and using this as a 'worst case' basis for the future. This approach is fine, as long as these claims are founded by comparing recent drought conditions to future climate change projections. However, the Hawkesdale study illustrates that in some cases such an approach may be inadequate and that rainfall and recharge under worst case climate change scenarios may be much less than under the drought conditions of recent years. If the worst case climate change scenario is realized, basing decisions on historical drought data may lead to underadaptation.
- *Conflict of interest* – short term versus long term interests, potential conflict of interest by decision makers.

- *Inadequate evaluation of adaptation options* – against economic, social and environmental criteria. Evaluation based only on current conditions, not the projected future environment.

None of the case studies have used an established framework for assessing vulnerability. In particular the case studies are lacking in a formal assessment and prioritization of risk. Whilst adaptations may be developed without a vulnerability assessment framework, there are significant benefits in doing so:

- It ensures that critical steps are incorporated into the decision making process.
- It allows users to analyze the elements of risk and to document the assumptions and priorities behind the risk assessment
- A sound understanding and documentation of the issues, objectives and likely risks helps to justify investment for adaptation.
- Prompts users to evaluate adaptation options against established criteria and objectives, to see if the desired outcomes will be met and if it is worthy of investment.

4.3 UK case study summary

Background

The United Kingdom case study (see larger report for full case study) considers the management of groundwater in East Anglia, in eastern England. East Anglia is the most intensively cultivated arable region in the UK. Groundwater is widely used for supplemental irrigation, as well as for residential and commercial purposes. While use for irrigation has been relatively stable, demand from other uses has been growing. With projected climate change, demand for irrigation is expected to increase and supply decrease, exacerbating pressures on resources.

Groundwater management arrangements

Groundwater is managed under the same general arrangements as surface water in the UK. Groundwater use has been managed in England for many decades. An abstraction license, issued by the Environment Agency, is required for uses exceeding 20 m^3/d. Historically, abstraction licenses were generally not time-limited, but all new licenses are time-limited normally to 12 years, although with a presumption of renewal (i.e. priority over new applicants provided water is available). Most abstraction licenses have cessation conditions attached which require abstraction to stop immediately if groundwater or river levels drop below a set threshold. Licenses are issued on a first-come first-served basis without prioritizing uses, but during droughts, priority for groundwater use is given to maintaining public water supply, then environment and finally irrigation.

Groundwater resources and climate change

Much of East Anglia is underlain by productive aquifers, in particular by the Cretaceous Chalk and younger Pliocene-Pleistocene Crag. Both are generally water table aquifers, although the overlying superficial deposits exert strong controls on groundwater flow and groundwater age. The Chalk is the most important aquifer within Great Britain.

Groundwater is used for domestic, industrial and commercial water supply, irrigation, environmental allocations and to support recreation. About 37% of water use is from groundwater. Across UK, only about 150 000 ha of agricultural land is irrigated, with usage accounting for about 160 000 ML of water in a 'dry' year. The licensed volume of groundwater abstraction for irrigation has declined in the east of England in recent years, although actual use has been stable for many years. Despite its small volumetric demand, irrigation is of significant economic importance to farmers, growers, and the food industry, improving crop yields, quality, consistency and reliability. Competition for groundwater is likely to increase in future, reflecting reduced supply due to projected climate change and growing demand from other sectors, including domestic use and environmental water provision.

Long-standing groundwater management legislation has meant that groundwater uses in East Anglia have been controlled. As a consequence there are no consistent long-term trends in groundwater resource status. Groundwater levels are generally controlled by the regional recharge and rise and fall in line with variations in rainfall. Although groundwater resources are stable, assessments have indicated that there is little groundwater available for further abstraction in many groundwater units.

Climate change is projected to have several direct impacts on groundwater in East Anglia. Drier summers and increased summer and autumn potential evapotranspiration are projected to delay the wetting up of soils and postpone commencement of the recharge season. With warming conditions, potential evapotranspiration is projected to be greater in spring, leading to more rapid drying of soils and a shortening of the recharge season. Reduced recharge in response to these factors may be at least partly offset by projected wetter conditions during winter, although recent work suggests there will be an overall reduction in groundwater recharge. Warmer and drier conditions during summer are likely to increase demand from all of the current uses. The need to reduce climate-induced stresses on vulnerable aquatic or groundwater-dependent terrestrial ecosystems could further reduce the availability of groundwater for use in irrigated agriculture.

Adaptation to climate change and hydrological variability

The water environment in the UK is heavily controlled, with the European Water Framework Directive the dominant influence. Its objective of achieving Good Ecological Status in all surface water bodies (and Good Status in groundwater bodies) by 2015 and beyond, and short-term economic pressures faced by agriculture, mean that few irrigators in eastern England are deliberately or specifically adapting to projected climate change. They and the abstraction licensing authority are adapting to water scarcity though in ways that should help them cope with the projected impacts of climate change. Adaptations include:

- Changes to the abstraction licensing system that enable adaptive management - a 6-yearly water resource planning cycle has been introduced to help ensure sustainable levels of abstraction are maintained in the face of changing supply conditions. Management arrangements ensure that abstraction decisions take place at a local level and that surface water and groundwater resources are managed conjunctively in each water management unit. License trading within management units is now permitted to encourage better utilization of scarce resources.
- Development of Water Abstractor Groups – the formation of such groups has empowered farmers to influence water policy and participate in resource management decision-making.
- Investment in more efficient irrigation technologies and better irrigation scheduling to reduce demand for water.
- Installation of on-farm reservoirs to capture and store surface flows in winter and provide alternative supplies to groundwater to help meet summer demand.
- Changes to land management to reduce water quality threats to groundwater resources from excessive use and leaching of nitrogenous fertilizers.

Discussion

While climate change is not a significant driver, a range of potential adaptations to water scarcity have been implemented in East Anglia. By helping to build the adaptive capacity of the irrigation sector and helping to reduce demand, they are developing resilience to observed climate variability and projected climate change.

Despite successes in implementation of adaptations, significant barriers or limitations exist. The short duration of abstraction licenses means that confidence among irrigators may be insufficient for the major capital investments to increase resilience. The combination of short-term economic uncertainties surrounding agricultural production, limited financial support from Regional Development Agencies and uncertainty over water availability also are barriers.

The sharing of water resources through water trading has yet to develop in the UK, even though legislation allows it. This reflects in part uncertainty over the processes involved and the greater simplicity of existing informal practices of renting or purchasing land with abstraction licenses that are used by farmers. The potential for water trading is large, as many abstraction licenses are never used and more are only partially used. Trading would allow water to be used where most needed. The danger however is that in areas where water resources are already under pressure, the re-activation of sleeper or unused license could cause an even greater conflict between the environment on the one side and the abstractors on the other.

Whilst the adaptation measures that have been discussed have increased the efficiency of utilization of groundwater, they have not fully exploited the abstraction opportunities afforded by better conjunctive use of surface and groundwater. It is suggested that adapting conjunctive use guidelines to make more use of the higher river flows in the "wetter" winters and saving groundwater for when rivers are low; and/or making better use of the difference in timing between high irrigation demand and low groundwater levels might further increase resilience.

The adaptation options already implemented are unlikely to be sufficient to cope with the range of future water resource outcomes anticipated by climate and socio-economic change. Given the likely increasing future demand for a diminishing resource, it is likely that further adaptation will be required, which might include further restriction of irrigation to the highest-value crops or a move to non-irrigated agriculture or livestock.

4.4 USA case study summary

Background

The case study (see larger report for full case study) considers improved management of groundwater supply to meet the future needs of residents of the township of Oro Valley (the Town) in the semi-arid south-west of the USA. Challenges associated with persistent drought conditions, which may be attributed to global climate change, are being incorporated into long-term water resource management planning by the Town.

Recent climate changes have resulted in decreased precipitation and surface runoff causing a significant drop in recharge to groundwater throughout south-western USA. Local groundwater resources have historically been the principal source of potable water supplies of the Town. Population growth is placing increasing demands on the groundwater supply. Ten years of persistent drought and the accompanying reduction in recharge to groundwater have caused water levels in the sole source aquifer to decline significantly. The drop in water levels and a reduction in well production capacity in some wells caused the Town to investigate groundwater availability and develop altered approaches to groundwater management.

Groundwater management arrangements

A water right is required in the State of Arizona to withdraw surface water or groundwater. Groundwater rights within the U.S. are managed individually by each of the fifty states. In Arizona, water rights are based on the doctrine of prior appropriation, which simply stated is a right of "first in time, first in right". A water right is generally required for industrial, irrigation, and municipal needs. Most domestic uses are exempt from obtaining a water right.

The transition from agricultural to urban population base is occurring in the region's major metropolitan areas, Tucson and Phoenix. This transition would not have been possible without allowing the transfer of water rights from agricultural (irrigation) to potable use. Many of the water rights for agriculture are very senior rights and typically the water rights are sold with the land. In these major metropolitan areas, groundwater is fully appropriated. So development is dependent on having the right to use the water.

In 1980, the State of Arizona adopted a *Groundwater Management Act* that includes the Assured Water Supply (AWS) program. The AWS program requires water service providers, including municipalities and developments located in unincorporated portions of the counties, to demonstrate that an AWS will be physically, legally, and continuously available for the next 100 years before the developer can record plats or sell parcels of land. The provider must prove that a 100-year groundwater supply is available by either satisfying the requirements to obtain a Certificate of Assured Water Supply or by a written commitment of a water service provider with a Designation of Assured Water Supply. Managed by the Arizona Department of Water

Resources (ADWR), this program has created a process that requires a study be completed to ensure that a long-term supply exists, that each successive AWS designation does not adversely impact pre-existing rights, and that recharge to the aquifer is considered (although potential impacts of climate change are not considered).

Groundwater resources and climate change

The Town of Oro Valley is located within the Basin and Range geographic province, which generally consists of north to south trending basins separated by north to south trending mountain ranges. The basin is about 8 km in width in the Oro Valley area, but extends to about 29 km north to the Falcon Valley area. The stream channel consists of basin-fill deposits, comprising granular sands and gravels that are highly permeable, readily accept streamflow infiltration, and therefore are optimum as a catchment area for recharge.

Recharge to the aquifer system in the area occurs from infiltration along adjacent mountain fronts, underflow from north-eastern parts of the Oro Valley area, and stream channel recharge along ephemeral drainage lines. Based on estimated recharge rates, average rates of groundwater recharge at the mountain fronts and stream channels in the Oro Valley vicinity are estimated at about 4.7 to 9.6 GL/y. Based on this range, average annual local groundwater recharge totals about 7.2 GL. The quantity of annual groundwater recharge is consequently reduced by the affects of drought.

Results of the study imply that there is an exponential rather than linear relationship between recharge and precipitation. As a result, mountain front recharge is believed to be sensitive to a relatively small reduction in precipitation. After 1995, when the average annual precipitation rate decreased to about 25 cm/y, it is anticipated that a significant reduction in recharge will occur. It is conjectured that stream channel recharge is similarly reduced as well. Actual reduction of natural groundwater recharge under persistent drought conditions remains unclear based on available data, but is considered to be significant.

Adaptation to climate change and hydrological variability

Adapting to uncertain changes in supply caused by multiple pressures, including climate change, has become a high priority. The impacts to groundwater caused by climate changes include declining water levels or other stresses that are not easily predictable and uncertain.

The use of groundwater by the Town is controlled by water rights (groundwater is fully appropriated) and groundwater regulations that affect Oro Valley and other water providers in the region that tap the same aquifer. Groundwater pumping has increased in the last 10 years at a faster rate than is being recharged, and groundwater levels are dropping. Model predictions indicate increased pumping will not sustain groundwater availability. Therefore the Town has developed, and is beginning to implement, multiple strategies that include water conservation, use of reclaimed water in lieu of potable water, improved storm water capture to enhance groundwater recharge, better engineered wells to improve capture and manage groundwater in a sustainable manner, shift water between sectors (agriculture to urban), and import surface water sources to supplement and reduce demand on groundwater.

The Town has taken significant steps to secure new water supply sources to alleviate the effects of over-drafting the groundwater aquifer system and impacts due to climate change. Current and future water resource planning and management adaptations include:

- groundwater development based on sustainability criteria;
- augment water supplies by importing reclaimed water and treated central Arizona project water;
- implementation of water conservation policies;
- enhance local groundwater recharge, including through improved storm water management.

All of these options consider technical, financial, legal, political, institutional, and environmental impacts. The Town is adopting impact fees to finance and implement current and future strategies.

4.5 Australian case study summaries

Two contrasting groundwater management case studies have been documented for Australia, the first relating to the Gnangara Mound in Western Australia and the second to the Hawkesdale Groundwater Management Area (GMA) in south-western Victoria. The Gnangara Mound is an important groundwater resource for the city of Perth, however it also supports groundwater dependent ecosystems with very high conservation value. The Hawkesdale GMA is in a largely rural region, with groundwater primarily used for irrigation and on-farm domestic and livestock use.

The case studies also illustrate differences in groundwater management arrangements between jurisdictions. Under Australia's constitution, groundwater management is the responsibility of State or Territory governments. This means that whilst there is general agreement between the different jurisdictions, individual governments have somewhat differing approaches to water allocation and planning. Consistent features of the approach include state ownership of water, with allocation of rights to access and use water being controlled by government. Allocation policies vary in detail but are all aligned on an approach to the sustainable allocation of groundwater in keeping with the concept of safe yield. Generally groundwater allocation for consumptive use will only be permitted where the resource can be maintained sustainably over the long term. Individual jurisdictions differ in the definitions of sustainability and in the legislative mechanisms that are available to manage allocation.

4.5.1 Management of the Gnangara Mound, Western Australia

Background

The Gnangara Mound case study considers the situation of a large shallow aquifer which has many ecological, social and economic demands. This aquifer and associated groundwater dependent ecosystems are highly sensitive to relatively small changes in storage volume. Management of water level is the key issue, given the range of interactions with the surface of the aquifer.

The Gnangara Mound is an area of sandy aquifer material that is open to direct groundwater recharge, located around and to the North of the city of Perth, Western Australia. It covers an area of approximately 2,200 km^2. The aquifer is underlain by shallow exposed sands and is largely dependent on rainfall recharge for water supply.

Groundwater management arrangements

The Department of Water is the manager of the State's water resources. It has the responsibility for planning and managing groundwater use on the Gnangara Mound for the benefit of the community. This involves identifying and protecting important groundwater dependent ecosystems and managing private and public water supply abstraction to protect those systems. The Department regulates the Water Corporation (the water retailer) and private use through licensing and monitors impacts on water levels and ecosystems.

Western Australia's Integrated Water Supply System (IWSS) is the key integrated system which provides potable water for Perth and surrounding areas. This system has relies heavily on water pumped from the Gnangara system. Approximately 45% of groundwater pumped from the Gnangara system is for the IWSS. Current management criteria also set out private groundwater allocation quotas of 60.6 GL/y from the Gnangara Mound.

Groundwater resources and climate change

The Gnangara Mound is a term used to describe an interconnected groundwater system that consists of three partially connected aquifers, the superficial (water table) aquifer (the Gnangara Mound proper), the Leederville aquifer and the Yarragadee aquifers. The latter two are deeper and generally confined aquifers that extend north and south of the superficial aquifer extent. The aquifers of the Gnangara system represent one of the largest sources of potable water in south-western Australia.

While abstraction of groundwater occurs across the system, impacts of abstraction predominantly manifest on the mound, that is, upon the shallow aquifer units. It is these shallow units that are most affected by changes in rainfall and hence by climate variability and change. The aquifer system is finely balanced and the response to changes in climate is likely to be felt in the short rather than long term, impacting for example a number of groundwater dependent wetlands that are already affected by recent dry weather.

Groundwater levels within the Gnangara Mound have been trending downwards for the last 30 years. The centre of the decline is largely within the central mound region where drawdown up to 6 m has occurred over this period. Typically drawdown is in the range of 1 to 2 m. This coincides with a general trend of declining annual rainfall across the south west of Western Australia. Abstraction and land use impacts on recharge are also implicated in declining groundwater levels. Climate change projections for the region are for further reductions in rainfall, with likely consequent impacts on recharge.

Adaptation to climate change and hydrological variability

Several measures have been introduced or are consideration to enable the Gnangara system to adapt to experienced climate change. Measures are directed at protecting important groundwater dependent ecosystems and maintaining supplies for consumptive uses. Adaptations identified include:

- Wetland supplementation – in which water is harvested from other locations and used to maintain wetland levels and ecological values. Two wetlands are currently supplemented on the Gnangara Mound, using water pumped from the shallow superficial and deeper Leederville aquifers.
- Cave system rehydration – during summer (when groundwater levels are lowest) re-hydration of a limestone caves system has been achieved by pumping water from a lake or from groundwater bores and using this to enhance recharge in the vicinity of caves. The increased recharge re-hydrates the caves and, by maintaining the end of summer levels, ecosystem function is supported.
- Limiting groundwater abstraction – licensed pumping is tightly controlled to limit the inter-annual fluctuation or the overall decline in the vicinity of wetlands. In some areas, superficial bores have been switched off in an effort to meet wetland water level criteria.
- Assessing managed aquifer recharge for the area – one project has trialed injection of reclaimed water (i.e. treated municipal effluent) into the deeper (Leederville) aquifer as a pilot to prove the feasibility of future injections. A trial is also planned for the superficial aquifer.
- Exploring alternative land uses after existing pine plantations are harvested – land use may be changed to enhance rainfall recharge in key areas that are currently in recharge deficit.
- Establishing a horticultural precinct using treated wastewater rather than potentially potable water from the Gnangara Mound.
- Changing land management (e.g. burning of *Banksia* woodlands) to increase recharge and maintain biodiversity values.
- Revising groundwater allocation to public and private water supplies.
- Development of the *Gnangara Sustainability Strategy (GSS)*[8], a whole of government approach to ensure the sustainable use of water for drinking and commercial purposes and to protect the environment. This strategy considers both water and land use impacts on the groundwater resource.

The major constraint on adaptation to changed climate conditions in the Gnangara Mound is the expectation of communities that water will always be available in the same quantities for consumptive use. In some cases lower water use activities are considered but in most of the examples, alternate sources of water are used to substitute for existing groundwater. This brings with it increased costs and lowered certainty of supply. In some cases lower quality water may need to be used.

As parts of Perth's metropolitan supply is now from desalinated sea water, there is an element of substitution of groundwater for "manufactured" water. This is an example where the ecological value of wetlands that were ground-

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[8] http://portal.water.wa.gov.au/portal/page/portal/gss

water fed is considered high enough to ensure that they are supplied by any available water.

4.5.2 *Hawkesdale Groundwater Management Area, Victoria*

Background

The Hawkesdale case study is also for a large volume aquifer system, but one in which recharge and use are currently considered to be approximately in balance. However this system may move out of balance due to climate change and would also do so if growing demand for groundwater for irrigated agriculture were to be satisfied.

Groundwater extraction is widespread across the Hawkesdale GMA. Approximately 2,300 bores are registered as possible extraction bores. Most are registered for stock and domestic use, with some used in dairies and for irrigation of pastures and fodder crops.

Groundwater management arrangements

The Victorian Government, through its water policy statement, *Our Water Our Future*, has made the commitment of bringing all the state's water resources under a sustainable water allocation regime. For groundwater, this means ensuring that all extraction falls within limits defined by the 'sustainable yield' of the aquifer. The sustainable yield is the renewable part of the groundwater resource, identified after making allowance for acceptable impacts on users, the surface environment and the resource itself.

Groundwater resources and climate change

The Hawkesdale GMA covers an area of approximately 1400 km^2. The Newer Volcanic Basalt (NVB), Port Campbell Limestone (PCL), Clifton Formation and Dilwyn Formation form the significant aquifers in the Hawkesdale GMA. Over much of the Hawkesdale GMA, the Narrawaturk Marl and Gellibrand Marl are considered aquitards that are believed to effectively hydraulically separate the Clifton Formation Aquifer from the underlying Dilwyn Formation Aquifer and the overlying PCL Aquifer respectively.

There is no groundwater monitoring of the key Port Campbell Limestone aquifer within the Hawkesdale GMA. Anecdotal evidence is provided by local groundwater users that suggests groundwater has been declining significantly for the past 5 years or so. This is consistent with a prolonged spell of relative dry conditions, which may reflect early signs of human-induced climate change.

Worst case climate change projections for the Hawkesdale GMA are for significantly less rainfall and recharge than has been experienced in the most recent (relatively dry) 10 year period. Temperatures are also projected to increase. Groundwater recharge is projected to decline by an even larger amount.

Adaptation to climate change and hydrological variability

Low rainfall over the past decade has resulted in several adaptive responses already being implemented by local groundwater users. These have primarily taken the form of changes in agricultural enterprise, although more direct measures have also been developed. Adaptations have included:

- Reducing the stocking rates and herd sizes for given properties to match the available feed (that can be produced without irrigation) to the grazing pressure.
- Introduce irrigation of fodder crops or pastures into the enterprise to reduce reliance on rainfall. As this is likely to put considerable pressure on groundwater resources this approach has not be favored by the water managers to date.
- Restrictions on the volume of licensed groundwater allocations offered to the public, through the relevant government agency reducing the availability of water licenses.
- Re-drilling and deepening bores which dry up as a result of reduced water levels.
- Targeting deeper aquifers which are confined and not as affected by direct recharge reduction.

Key barriers to adaptation are around the ability to develop profitable farm enterprises that can operate in a reduced rain environment, or at best a reduced security of rainfall.

The key adaptive changes for this area are in policy responses to water allocation, including:

- groundwater allocation limits – new (lower) limits will need to be set in light of the likely reduction in available recharge. As with the Gnangara Mound case study, this area is likely to see reductions in recharge resulting from climate change;
- incorporation of uses of groundwater that have not so far been incorporated – in this area there is a potential for significant water use by plants, especially from forestry plantations that have been established in parts of the GMA over the last decade. Currently the relevant State government department is considering policy responses to water use by plantations.
- acknowledging the role of land use – land use dictates the pattern of recharge for the Hawkesdale area. Changes in land use, such as forestry plantations and/or cropping and/or irrigation will significantly change the recharge pattern. This in turn will have implications for recharge and hence the available resources.

5. CONCLUSION

Compared to surface water, groundwater is much more compatible with a highly variable and changing climate. Aquifers have the capacity to store large volumes of water and are naturally buffered against seasonal changes in temperature and rainfall. They provide a significant opportunity to store excess water during high rainfall periods, to reduce evaporative losses and to protect water quality.

Groundwater is a critical component of adapting to hydrologic variability and climate change. Groundwater options for enhancing the reliability of water supply for domestic, industrial, livestock watering and irrigation include (but are not exclusive to):

- *Integrating the management of surface water and groundwater resources* – including conjunctive use of both groundwater and surface water to meet water demand. Integrated management aims to ensure that the use of one water resource does not adversely impact on the other. It involves making decisions based on impacts for the whole hydrologic cycle.
- *Managing aquifer recharge (MAR)* – including building infrastructure and/or modifying the landscape to intentionally enhance groundwater recharge. MAR is among the most promising adaptation opportunities for developing countries. It has several potential benefits, including storing water for future use, stabilizing or recovering groundwater levels in over-exploited aquifers, reducing evaporative losses, managing saline intrusion or land subsidence, and enabling reuse of waste or storm water.
- *Land use change* – changing land use may provide an opportunity to reduce groundwater losses from evapotranspiration, to enhance recharge, and to improve groundwater quality. Changes in land use should not result in adverse impacts to other parts of the environment.

Groundwater is also vulnerable to climate change and hydrological variability. Potential climate risks for groundwater include reduced groundwater recharge, sea water intrusion to coastal aquifers, contraction of freshwater lenses on small islands, and increased demand. Groundwater can also be affected by non-climatic drivers, such as population growth, food demand and land use change. Active consideration of both climatic and non-climatic risks in groundwater management is vital.

Effective, long term adaptation to climate change and hydrologic variability requires measures which protect or enhance groundwater recharge *and* manage water demand. Adaptation to climate change can't be separated from actions to improve management and governance of water reserves (e.g. education and training, information resources, research and development, governance and institutions).

Adaptation needs to be informed by an understanding of the local context, and of the dominant drivers (and their projected impact) on groundwater resources in the future. Adaptations must be carefully assessed to ensure investment in responses to climate change and hydrological variability is proportional to risk and that they do not inappropriately conflict with other social, economic, resource management or environmental objectives. Adaptations should not add further pressures on the global climate system by significantly increasing greenhouse gas emissions.

Adaptation options need to be economically viable. In some cases the cost and benefits of an adaptation option may warrant introducing fees/charges for groundwater use, so that an appropriate level of cost recovery is met. An economic assessment of adaptation options should factor any initial and ongoing costs, and means for financing these. It must also take into account the local economic environment, which can vary significantly between and within nations.

In many cases, adaptations to reduce the vulnerability of groundwater dependent systems climatic pressures are the same as those required to address

non-climatic pressures, such as over-allocation or overuse of groundwater. Such 'no regrets' adaptations can be implemented immediately in areas where water resources are already stressed, regardless of concerns about the uncertainty of climate change projections and assessments of impact on groundwater and surface water resources.

Successful examples of groundwater adaptation to climate change and hydrologic variability exist in both developed and developing nations. A list of available adaptation options is included in Section 3 of this report. Summaries of adaptation case studies from three developed nations (England, America and Australia) are provided in Section 4.

6. RECOMMENDATIONS

To improve the capacity for and uptake of groundwater adaptation, the following recommendations are made:

1. **Support adaptation case studies from developing nations** – adaptation case studies from three developed nations were reviewed in the current report. As part of the global groundwater governance project and the Bank's sector analysis on groundwater governance project, a series of case studies and evaluations should be prepared for developing countries. Possible case study countries could include: Peru, India, Kenya, Mexico, Morocco, Tunisia, South Africa, Tanzania and Yemen. Transboundary aquifers might also be considered, potentially including:
    - the Nubian sandstone aquifer system – this aquifer is located in north-eastern Africa and spans the political boundaries of four countries: Chad, Egypt, Libya and Sudan;
    - aquifers that span across the fourteen countries in the South African Development Community (SADC)

    These case studies would provide guidance to water resource managers in similar settings on improving groundwater governance and conceptualizing and implementing adaptation programs. As a minimum the case studies should focus on examples of MAR, improved management of groundwater storages, conjunctive planning and management of groundwater and surface water and reform of water governance.

    The case studies should cover a range of biophysical and institutional settings and be representative of different kinds of experienced climate change or climate risk impact.
2. **Promote groundwater management and development opportunities** – identify and integrate opportunities to manage and develop groundwater in future water sector programs to improve the reliability of water supply. This may include supporting:
    - Assessments of climate vulnerability.
    - Assessment of the suitability of MAR – to determine the potential viability for MAR. This assessment should identify areas of current water stress (i.e. need), water availability (e.g. excess wet season surface flows, treated waste water), potential storage, and the likelihood that groundwater quality will be suitable for the required use/s.

      If MAR is deemed viable, subsequent tasks should include:
        - Identification and prioritization of water stressed areas, particularly focusing on areas of current or foreseeable shortages in drinking water supply.
        - Mapping of MAR potential within the identified priority areas. If possible, this should be undertaken at a 1:100,000 to 1:250,000 scale. This will help prioritize areas for site specific investigation and demonstration projects. Suggested criteria for mapping MAR potential are summarized in Section 3.4.1.
        - Identification of institutions that may take responsibility for regulation, licensing and monitoring of MAR schemes
        - Identification of potentially suitable types of MAR, mindful that in developing countries the most successful, low risk MAR schemes are likely to be of simple technology and low cost. Examples of different MAR schemes are provided in Section 3.4.1.

      Any planning for MAR should be coupled with demand management strategies.
    - Capacity building in groundwater management and planning. This may include activities such as groundwater resource assessments to better understand the resource, establishing and populating groundwater databases, increasing the level of hydrogeological expertise by establishing or improving accessibility to groundwater training institutions, a manual for groundwater management to outline minimum good practice standards etc.
    - More integrated management of water resources. This may include conjunctive water use and assessing the impacts of existing or proposed infra-

structure to identify any potential inefficiencies or adverse impacts that may be treated to achieve optimal use of water resources.

3. **Disseminate knowledge** – Information from this report and developing country case studies should be disseminated to World Bank staff as part of the overall sector analysis on Climate Change and Water.
4. **Collaborate with programs and partner agencies with specialized knowledge** – including:
    - Groundwater Resources Assessment under the Pressures of Humanity and Climate Change (GRAPHIC) – the GRAPHIC project is hosted by IHP UNESCO, IGRAC and GWSP and focuses on understanding the impacts of climate change and other pressures for groundwater, globally;
    - International Association of Hydrogeologists (IAH), and
    - International Groundwater Resource Assessment Centre (IGRAC)

7. GLOSSARY OF TERMS

(Source: Bates et al, 2008, except where noted)

Adaptation

Initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects. Various types of adaptation exist, e.g. anticipatory and reactive, private and public, and autonomous and planned. Examples are raising river or coastal dikes, the substitution of more temperature-shock resistant plants for sensitive ones, etc.

Adaptive capacity

The whole of capabilities, resources and institutions of a country or region to implement effective adaptation measures.

Aquifer

A rock formation, group of rock formations, or part of a rock formation that combines sufficient permeable material to yield economical quantities of water to wells and springs.

Climate

Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.

Climate change

Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the United Nations Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods'. The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes.

Climate model

A numerical representation of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes, and accounting for all or some of its known properties. The climate system can be represented by models of varying complexity, that is, for any one component or combination of components a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical or biological processes are explicitly represented, or the level at which empirical parameterisations are involved. Coupled Atmosphere-Ocean General Circulation Models (AOGCMs) provide a representation of the climate system that is near the most comprehensive end of the spectrum currently available. There is an evolution towards more complex models with interactive chemistry and biology. Climate models are applied as a research tool to study and simulate the climate, and for operational purposes, including monthly, seasonal and interannual climate predictions.

Climate projection

A projection of the response of the climate system to emissions or concentration scenarios of greenhouse gases and aerosols, or radiative forcing scenarios, often based upon simulations by climate models. Climate projections are distinguished from climate predictions in order to emphasize that climate projections depend upon the emission/concentration/radiative forcing scenario used, which are based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realised and are therefore subject to substantial uncertainty.

Climate scenario

A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. Climate projections often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information such as about the observed current climate. A climate change scenario is the difference between a climate scenario and the current climate.

Climate system

The climate system is the highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the land surface and the biosphere, and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations and anthropogenic forcings such as the changing composition of the atmosphere and land-use change.

Climate variability

Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).

Confidence

As defined by the IPCC, the degree of confidence in being correct is described as follows:

Very high confidence	At least 9 out of 10 chance of being correct
High confidence	About 8 out of 10 chance
Medium confidence	About 5 out of 10 chance
Low confidence	About 2 out of 10 chance
Very low confidence	Less than a 1 out of 10 chance

Coping range

The range within which a system has the capacity to cope with some level of variability (in this case to climate or hydrology) without impairment.

Detection and attribution

Climate varies continually on all time scales. ***Detection*** of climate change is the process of demonstrating that climate has changed in some defined statistical sense, without providing a reason for that change. ***Attribution*** of causes of climate change is the process of establishing the most likely causes for the detected change with some defined level of confidence.

Downscaling

Downscaling is a method that derives local-to regional-scale (10 to 100km) information from larger-scale models or data analyses. Two main methods are distinguished: dynamical downscaling and empirical/statistical downscaling. The dynamical method uses the output of regional climate models, global models with variable spatial resolution or high-resolution global models. The empirical/statistical methods develop statistical relationships that link the large-scale atmospheric variables with local/regional climate variables. In all cases, the quality of the downscaled product depends on the quality of the driving model.

Emissions scenario

A plausible representation of the future development of emissions of substances that are potentially radiatively active (e.g., greenhouse gases, aerosols), based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socioeconomic development, technological change) and their key relationships. Concentration scenarios, derived from emission scenarios, are used as input to a climate model to compute climate projections. In IPCC (1992) a set of emission scenarios was presented which were used as a basis for the climate projections in IPCC (1996). These emission scenarios are referred to as the IS92 scenarios. In the IPCC Special Report on Emission Scenarios (Nakićenović and Swart, 2000) new emission scenarios, the so-called SRES scenarios, were published.

Ensemble

A group of parallel and model simulations used for climate projections. Variation of the results across the ensemble members gives an estimate of uncertainty. Ensembles made with the same model but different initial conditions only characterise the uncertainty associated with internal climate variability, whereas multi-model ensembles including simulations by several models also include the impact of model differences. Perturbed-parameter ensembles, in which model parameters are varied in a systematic manner, aim to produce a more objective estimate of modelling uncertainty that is possible with traditional multi-model ensembles.

Exposure

In the context of this report, exposure refers to groundwater dependent systems being subjected to adverse affects of climate change and hydrologic variability.

Evapotranspiration

Loss of water to the atmosphere via direct evaporation or transpiration by vegetation.

Flexibility

The flexibility of a system refers to its ability to adapt to a wide range of operating conditions through relatively modest and inexpensive levels of redesign, refitting or reoperation (Hashimoto, T. et al., 1982a).

General Circulation Model

See *Climate model*.

Greenhouse effect

Greenhouse gases effectively absorb thermal infrared radiation, emitted by the Earth’s surface, by the atmosphere itself due to the same gases, and by clouds. Atmospheric radiation is emitted to all sides, including downward to the Earth’s surface. Thus greenhouse gases trap heat within the surface troposphere system. This is called the greenhouse effect. Thermal infrared radiation in the troposphere is strongly coupled to the temperature of the atmosphere at the altitude at which it is emitted. In the troposphere, the temperature generally decreases with height. Effectively, infrared radiation emitted to space originates from an altitude with a temperature of, on average, –19°C, in balance with the net incoming solar radiation, whereas the Earth’s surface is kept at a much higher temperature of, on average, +14°C. An increase in the concentration of greenhouse gases leads to an increased infrared opacity of the atmosphere, and therefore to an effective radiation into space from a higher altitude at a lower temperature. This causes a radiative forcing that leads to an enhancement of the greenhouse effect, the so-called enhanced greenhouse effect.

Greenhouse gas (GHG)

Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere. Moreover, there are a number of entirely human-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine and bromine containing substances, dealt with under the Montreal Protocol. Beside CO_2, N_2O and CH_4, the Kyoto Protocol deals with the greenhouse gases sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).

Groundwater

The water contained in interconnected pores, gaps or fractures located below the water table in an unconfined aquifer, or in a confined aquifer.

Groundwater dependent systems

Those systems that rely on groundwater for survival, including human populations, industries (e.g. agriculture) and ecosystems.

Groundwater development

The abstraction of groundwater for human use.

Groundwater discharge

The process by which water is lost from groundwater, including evapotranspiration, flow to streams, springs, wetlands and oceans, and pumping from wells.

Groundwater management

The management of groundwater resources to meet established objectives for the water resource. Example objectives include: ensuring availability of the groundwater resource into the future, meeting environmental water requirements, meeting water quality criteria to be able to provide potable water supply, etc.

Groundwater recharge

The process by which water from the surface enters the groundwater system.

Hydrological cycle

The cycle in which water evaporates from the oceans and the land surface, is carried over the Earth in atmospheric circulation as water vapour, condensates to form clouds, precipitates again as rain or snow, is intercepted by trees and vegetation, provides runoff on the land surface, infiltrates into soils, recharges groundwater, discharges into streams, and ultimately, flows out into the oceans, from which it will eventually evaporate again (AMS, 2000). The various systems involved in the hydrological cycle are usually referred to as hydrological systems.

(Climate change) Impacts

The effects of climate change on natural and human systems. Depending on the consideration of adaptation, one can distinguish between potential impacts and residual impacts:

- *Potential impacts*: all impacts that may occur given a projected change in climate, without considering adaptation.
- *Residual impacts*: the impacts of climate change that would occur after adaptation.

Likelihood

As defined by the IPCC, the likelihood of the occurrence/ outcome is described below:

Virtually certain	>99% probability of occurrence
Very likely	90 to 99% probability
Likely	66 to 90% probability
About as likely as not	33 to 66% probability
Unlikely	10 to 33% probability
Very unlikely	1 to 10% probability
Exceptionally unlikely	<1% probability

Managed aquifer recharge

Involves building infrastructure and/or modifying the landscape to intentionally enhance groundwater recharge.

Mitigation

Technological change and substitution that reduce resource inputs and emissions per unit of output. Although several social, economic and technological policies would produce an emission reduction, with respect to Climate Change, mitigation means implementing policies to reduce greenhouse gas emissions and enhance sinks.

No-regrets policy

A policy that would generate net social and/or economic benefits irrespective of whether or not anthropogenic climate change occurs.

Palaeoclimate

Climate for periods prior to the development of measuring instruments, for which only proxy climate records (such as may be determined from tree rings, geology, or ice cores) are available.

Projection

A potential future evolution of a quantity or set of quantities, often computed with the aid of a model. Projections are distinguished from predictions in order to emphasize that projections involve assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realised, and are therefore subject to substantial uncertainty.

Reliability

Reliability is defined as the likelihood that services are delivered (no failure) within a given period, expressed as a probability. High probabilities indicate high reliability (Hashimoto, T. et al., 1982b).

Resilience

A. The ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organization, and the capacity to adapt to stress and change.

B. Resiliency is the speed at which the system recovers from a failure, on average. Shorter recovery periods indicate higher resiliency (Hashimoto, T. et al., 1982b).

Risk

The potential for realization of unwanted, adverse consequences; usually based on the expected result of the conditional probability of the occurrence of the event multiplied by the consequence of the event, given that it has occurred.

What makes a situation risky rather than uncertain is the availability of objective estimates of the probability distribution. (USACE, 1992)

Robustness

In a water resources system, robustness refers to the extent to which a system design is able to deliver optimal or near-optimal levels of service over a range of demand (input) and supply (resource) conditions (Hashimoto, T. et al., 1982a).

Scenario

A plausible and often simplified description of how the future may develop, based on a coherent and internally consistent set of assumptions about driving forces and key relationships. Scenarios may be derived from projections, but are often based on additional information from other sources, sometimes combined with a narrative storyline.

Sensitivity

Sensitivity is the degree to which a system is affected, either adversely or beneficially, by

climate variability or climate change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea level rise).

Stationarity

Stationarity assumes that natural systems fluctuate within an unchanging envelope of variability. Stationarity is a foundational concept that permeates training and practice in water-resource engineering. It implies that any variable (e.g., annual streamflow or annual flood peak) has a time-invariant (or 1-year–periodic) probability density function (pdf), whose properties can be estimated from the instrument record. Under stationarity, pdf estimation errors are acknowledged, but have been assumed to be reducible by additional observations, more efficient estimators, or regional or paleohydrologic data. The pdfs, in turn, are used to evaluate and manage risks to water supplies, waterworks, and floodplains (Milly et al., 2008).

Threshold

The level of magnitude of a system process at which sudden or rapid change occurs. A point or level at which new properties emerge in an ecological, economic or other system, invalidating predictions based on mathematical relationships that apply at lower levels.

Uncertainty

A. An expression of the degree to which a value (e.g., the future state of the *climate system*) is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from quantifiable errors in the data to ambiguously defined concepts or terminology, or uncertain *projections* of human behaviour. Uncertainty can therefore be represented by quantitative measures, for example, a range of values calculated by various models, or by qualitative statements, for example, reflecting the judgment of a team of experts.

B. Uncertain situations are those in which the probability of potential outcomes and their results cannot be described by objectively known probability distributions, or the outcomes themselves, or the results of those outcomes are indeterminate (USACE, 1992)

United Nations Framework Convention on Climate Change (UNFCCC)

The Convention was adopted on 9 May 1992 in New York and signed at the 1992 Earth Summit in Rio de Janeiro by more than 150 countries and the European Community. Its ultimate objective is the “stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". It contains commitments for all Parties. Under the Convention, Parties included in Annex I (all OECD member countries in the year 1990 and countries with economies in transition) aim to return greenhouse gas emissions not controlled by the Montreal Protocol to 1990 levels by the year 2000. The Convention entered in force in March 1994.

Vulnerability

A. Vulnerability is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity.

B. Vulnerability refers to the severity of the likely or expected consequences of failure (Hashimoto, T. et al., 1982b).

Water table

The surface between the unsaturated and saturated zones of the subsurface at which the hydrostatic pressure is equal to that of the atmosphere.

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